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Water Mist Flashover Suppression and Boundary Cooling System for Integration with DC-ARM Volume I: Summary of Testing

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<p>This report describes the results of the first year of an experimental program aimed at developing a prototype water mist fire suppression (WMFS) system for integration with DC-ARM (Damage Control—Automation for Reduced Manning) objectives on Navy shipboard applications. The WMFS system is to provide, as a minimum, flashover suppression and boundary cooling, so that a fire may be controlled and confined to the compartment of origin for an extended period. Damage control crews responding to the fire will encounter small fires, which can be extinguished using a minimum of manpower. In this way the number of persons required for Damage Control response will be reduced from current levels. The WMFS system is to be designed to be reflexive, so that battle damage to piping will be self-isolated to the area of direct damage, leaving the surrounding parts of the distribution system in operable condition.</p>			
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WATER MIST FLASHOVER SUPPRESSION AND BOUNDARY COOLING SYSTEM FOR INTEGRATION WITH DC-ARM

VOLUME I: SUMMARY OF TESTING

1.0 INTRODUCTION

The strategy for the DC ARM Water Mist development work was to first quantify characteristics of water mists produced by a range of commercially available mist nozzles (Task 1), then to conduct fire tests to measure the ability of mist produced by those nozzles to mitigate fire conditions in ship compartments (Task 2). The Task 1 data will be used to match generic mist characteristics to the ability to mitigate fire and smoke damage, which in turn will contribute to decision-making with respect to system design. The primary objective of the Task 2 fire testing was to determine what level of protection could be achieved using very low application rates of water mist. The performance target was not set at fire extinguishment, but rather at preventing fire conditions from advancing to flashover in the compartment of fire origin—"flashover suppression" in the terminology of the Experiment Plan. "Flashover" is the phenomenon that occurs when all combustibles in the compartment have been heated to ignition and the compartment becomes fully involved in flame. "Flashover suppression" can be achieved by mixing fine water spray with the hot gases in the compartment so that they are cooled to the point that no other combustibles in the compartment are raised to ignition temperature.

This report summarizes the results of the work done under Tasks 1 and 2 of the Experiment Plan. It discusses the value of the results relative to developing design criteria for a water mist system for integration with DC ARM on Navy ships.

2.0 SPRAY CHARACTERIZATION

Task 1: Characterize sprays produced by selected commercially available water mist nozzles, according to drop size distribution, cone angle and flux density distribution, and hydraulic factors (pressure-discharge) as well as spray velocity and momentum.

The important qualities of a spray relative to performance as a fire suppressant include the drop size distribution, the mass discharge rate as a function of pressure; cone angle and distribution pattern; and the initial spray velocity [1]. Measurements were taken to quantify these qualities for the purpose of comparing sprays produced by several nozzles selected for use in the test series. Nozzles manufactured by Grinnell, Kidde International, Marioff, and Spraying Systems Company were selected.

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The nozzles selected were developed by their manufacturers for applications against Class B fuels in machinery spaces. In general, they produce a higher mass fraction of fine drops than sprays intended for Class A fires, as this was found to be an advantage throughout the fire testing programs to which they were tested. For this DC ARM water mist system testing, however, the focus is on applications other than machinery spaces, such as berthing areas on ships, which are typically Class A fuel scenarios. Extinguishment of Class A materials is known to benefit from fuel wetting, achieved by larger drops landing directly on the fuel. The same manufacturers listed above have developed nozzles with drop size distributions suitable for Class A fuel fire scenarios. The test objective in this test series, however, was to examine "flashover suppression" in compartments containing Class A fuels, rather than extinguishment of those Class A fuels. Flashover suppression is achieved by cooling hot gases so that the compartment cannot become hot enough to result in general ignition of all combustibles [2,3]. Because a spray with higher fraction of fine droplets is likely to be more effective at gas phase cooling than a spray with a lower fraction, the machinery space nozzles were selected for Task 2 fire testing.

2.1 Nozzle Descriptions

2.1.1 Grinnell Aquamist

Grinnell's Aquamist AM10 machinery room mist nozzle is a low-pressure, single-fluid nozzle, designed to operate at 12 bar. A jet of water issuing from a 2.5 mm orifice impinges on a spherical surface to create a water mist with approximately a 90 degree cone angle. The manufacturer reports a K factor of $3.5 \text{ L/min/bar}^{1/2}$. The nozzle can be equipped with a thermally sensitive bulb element to allow it to activate like a standard sprinkler.

Two other Grinnell water mist nozzles, the AM4, and the AM6, were examined for spray characteristics. The AM4 is similar to the AM10 nozzle, with the same size orifice and K factor. The deflector surface is different, however, consisting of a small diameter indented disk rather than a sphere. The AM6 nozzle has a larger orifice (4 mm) with a K factor of $4.7 \text{ L/min/bar}^{1/2}$. The nominal flow rate is 34 percent higher than the AM10 machinery space nozzle. Although of interest for testing for boundary cooling objectives, neither the AM4 or AM6 was used in the Task 2 fire testing.

Nozzle Designation	Description	K Factor	Design Pressure	Flow Rate
Aquamist AM10	Low-pressure, single fluid Impingement nozzle; 90° cone	$3.5 \text{ L/min/bar}^{1/2}$	12 bar	12.1 L/min
Aquamist AM4	Low-pressure, single fluid Impingement nozzle; 90° cone	$3.5 \text{ L/min/bar}^{1/2}$	12 bar	12.1 L/min
Aquamist AM6	Low-pressure, single fluid Impingement nozzle; 90° cone	$4.7 \text{ L/min/bar}^{1/2}$	12 bar	16.3 L/min

2.1.2 Kidde International

Three nozzles were received from Kidde Deugra of Germany, for fire testing. The nozzle operates by directing five very fine streams of water to collide with each other, several millimeters in front of the orifice. The mist formation mechanism is therefore partially a “pressure jet” and an impingement mechanism. It is expected that the impingement event increases the energy available for atomization and introduces random directionality to the mist particles. The spray characteristics of all three nozzles were measured. The ESK 1215 nozzle was not used in fire testing.

Nozzle Designation	Description	K Factor	Design Pressure	Flow Rate
ESK 1214 (K14)	Low-pressure, single fluid Impinging jets; 90° cone	1.3 L/min/bar ^{1/2}	12 bar	4.5 L/min
ESK 1215 (K15)	Low-pressure, single fluid Impinging jets; 90° cone	1.6 L/min/bar ^{1/2}	12 bar	5.5 L/min
ESK 8563 (K63)	Low-pressure, single fluid Impinging jets; 90° cone	2.9 L/min/bar ^{1/2}	12 bar	10.0 L/min

2.1.3 Marioff Hi-Fog

Two Marioff nozzles were investigated, designated “4S 1MC 8MB 1100,” and “3S 1MB 4MB 1000.” The nozzle is a high-pressure, single-fluid device, which mounts multiple individual orifices on a machined metal body. The “4S 1MC 8MB 1100” nozzle is listed for use in turbine enclosures and machinery spaces. The digits ‘1100’ at the end of the code indicate it is an FM listed nozzle; “1000,” that it is not. The “4” indicates it is a 90-degree cone; ‘1MC’ indicates that there is one orifice on the central axis, with diameter 1.0 mm; ‘8MB’ indicates there are 8 orifices equally spaced around the body of the nozzle, each with diameter 0.7 mm. The ‘3’ in the designation for the second nozzle indicates it has a 120 degree spray cone, one central orifice of diameter 0.7 mm, and four 0.7-mm orifices around the body of the nozzle.

Nozzle Designation	Description	K Factor	Design Pressure	Flow Rate
4S 1MB 8MC 1100	High-pressure, single fluid Pressure jet; 90° cone	1.9 L/min/bar ^{1/2}	70 bar	15.9 L/min
3S 1MB 4MB 1000	High-pressure, single fluid Pressure jet; 90° cone	1.0 L/min/bar ^{1/2}	70 bar	8.4 L/min

2.1.4 Spraying Systems Company (NAVY) Nozzle

The fourth nozzle was a customized Spraying Systems Company 7N series nozzle, which was developed for machinery spaces on the Navy's LPD17 [4]. It consists of a Spraying Systems Company Model 7N nozzle with some modifications. For typical Navy machinery space installations, two orifice arrangements are provided, one for ceiling mounted nozzles, and one for nozzles mounted at an intermediate level. This test series used the one developed for ceiling mounting. It has seven orifices in all. Six 1/4LN2 orifice caps (CP1206 and CP1207-2-SS) with 1/4LN26 orifice inserts (3781-26) are installed around the perimeter of the nozzle. A 1/4LN12 orifice cap assembly with a 1/4LN12 orifice insert is installed in the center of the group. The nominal K factor was measured previously [4], as $1.43 \text{ L/min/bar}^{1/2}$, producing a flow of 13.25 L/min at a 70 bar nozzle pressure.

The capabilities of the Navy nozzle system were evaluated during numerous full-scale machinery space tests [5, 6]. The nozzle has not been evaluated as part of a 'listing.'

Nozzle Designation	Description	K Factor	Design Pressure	Flow Rate
NAVY	High-pressure, single fluid Pressure jet; 120° cone	$1.6 \text{ L/min/bar}^{1/2}$	70 bar	13.3 L/min

2.2 Measurement Methods

2.2.1 Flow and Pressure

Measurements for the low-pressure nozzles (AM10 and K14) were taken in a test room constructed in the laboratory at Hughes Associates, Inc., in Baltimore. Characterizations for the two high-pressure nozzles, MF11 and the Navy nozzle, were conducted at the Task 2 test room in the Naval Research Laboratory's (NRL's) Calorimetry lab at Chesapeake Beach Detachment (CBD). In both locations all measurements were taken at a distance of 1.0 m below the nozzle. Spray characteristics were measured at the same location for all nozzles, so that comparisons can be made.

Figure 1 shows the arrangement of equipment used to measure spray characteristics. Water pressure and flow rate could be monitored while the flux density, velocity or drop size distribution measurement occurred. Water flow for the single nozzle set-up was accomplished using a Sponsler 12 mm (1/2 in.) Turbine Type Flow Meter with 4-20 mA output (SP 712-2), 4.73 – 36.0 L/min range (SP 1/2 -MB-PHL-A-4-X + SP 712-2). For larger flows associated with

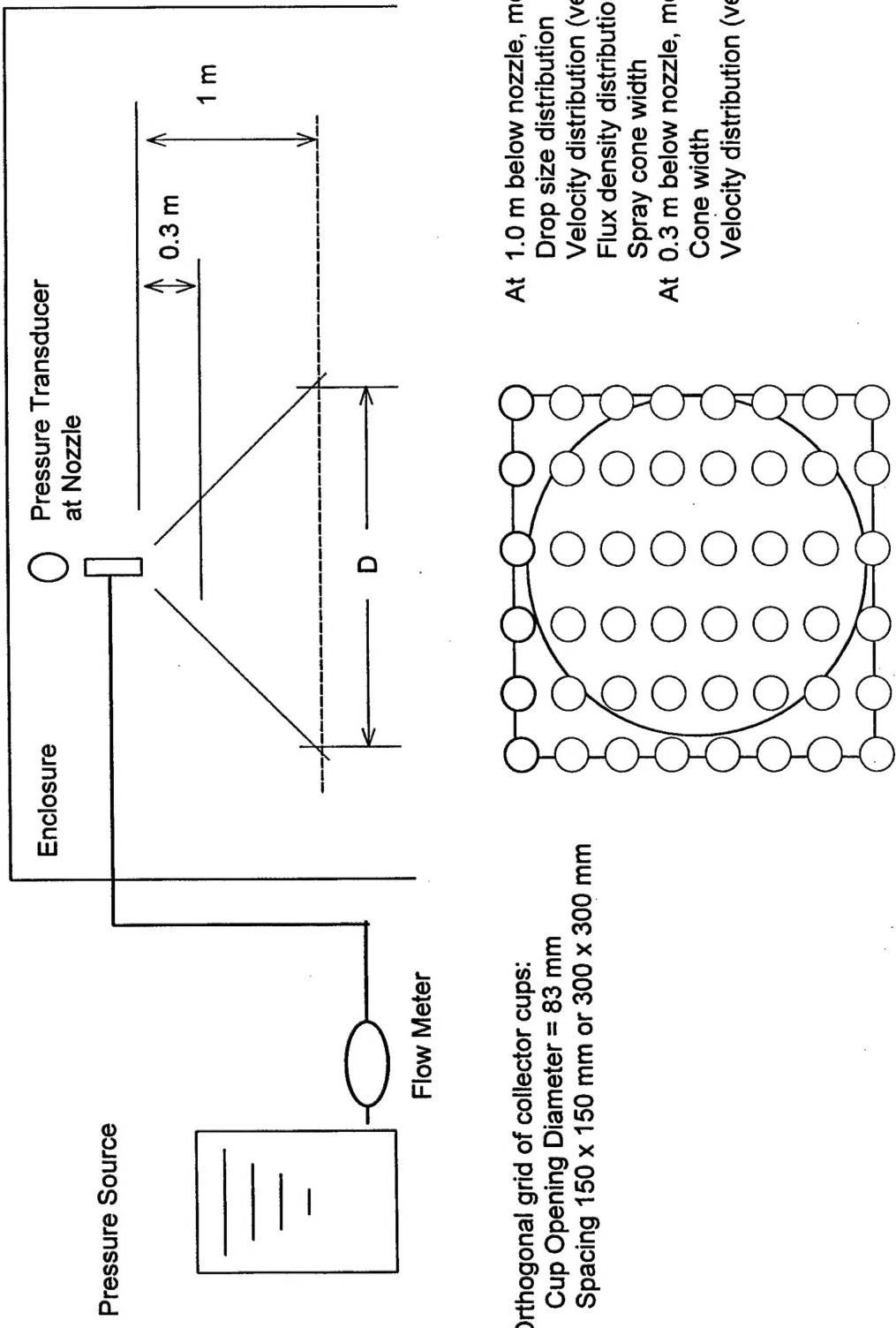


Fig. 1 - Equipment and arrangement for measuring flux density distributions and pressure/flow relationships

groups of nozzles, two SP ½ -MB flow meters were connected in parallel to extend the range to 72 L/min while maintaining the same precision as for 36 L/min readings (1 L/min).

Pressure transducers selected for the appropriate high- or low-pressure range recorded the pressure at the nozzle. An Omega PX725-3KGI transducer was used for the high pressure nozzles, 34 to 210 bar. For low pressure nozzles, an Omega PX725-500GI transducer was used. Transducers were protected against shock pressures by means of a restricted orifice installed in the connection fitting.

From measurements of flow over a range of pressures, it was possible to obtain a linear best fit curve for the relationship between Q (flow) and P (pressure). That best-fit data were used to plot Q as a function of the square root of P. The slope of that line was then taken as the "K factor" characteristic of the nozzle.

It is reasonable to expect that there is a relationship between the energy that a spray introduces into a compartment and its ability to change gas flows, cause mixing and cool gases. The amount of energy expended on spray generation will be reflected in particle sizes, mass flow rate, spray velocity, air entrainment and mixing. Nozzle energy can be approximately quantified by converting the mass flow rate and nozzle pressure to an energy term, or "power coefficient." A simple way to do this is to treat the Q-P information on the nozzle as a pumping issue. If we ignore efficiency, the power required to pump Q-L/min at a pressure of P-bar, in kilowatts, is

$$\text{Power Coefficient } PC = (Q \times P)/600$$

Power coefficients are tabulated for each nozzle in Table 1 (see Section 2.3). This simple parameter is proposed as a quantification of the energy characteristics of the spray. Whether there is any value in this term as an indicator of performance or potential design parameter will be tested through examination of the Task 2 fire test results.

2.2.2 Flux Density Distribution

Flux density was measured by recording the time to collect water in arrays of collector cups placed beneath the nozzles. One of the primary uses of the flux density data was as a weighting factor for the drop-size distribution measurements. It was important therefore to be able to specify the flux density at each location in the spray where the drop size was to be measured. Two methods were used. The simplest was to arrange collector cups, spaced 150 mm apart, on the two axes to be used for the drop size measurement (see Figure 2). This method provided information to plot a flux density profile on specific axes. A more comprehensive method of measurement involved laying out an orthogonal grid of collector cups as shown in Figure 1, spaced 150 mm or 300 mm apart, depending on the dimensions of the spray cone. Up to 144 cups were used, to provide sufficient data to permit plotting two and three dimensional contours of the flux density distribution.

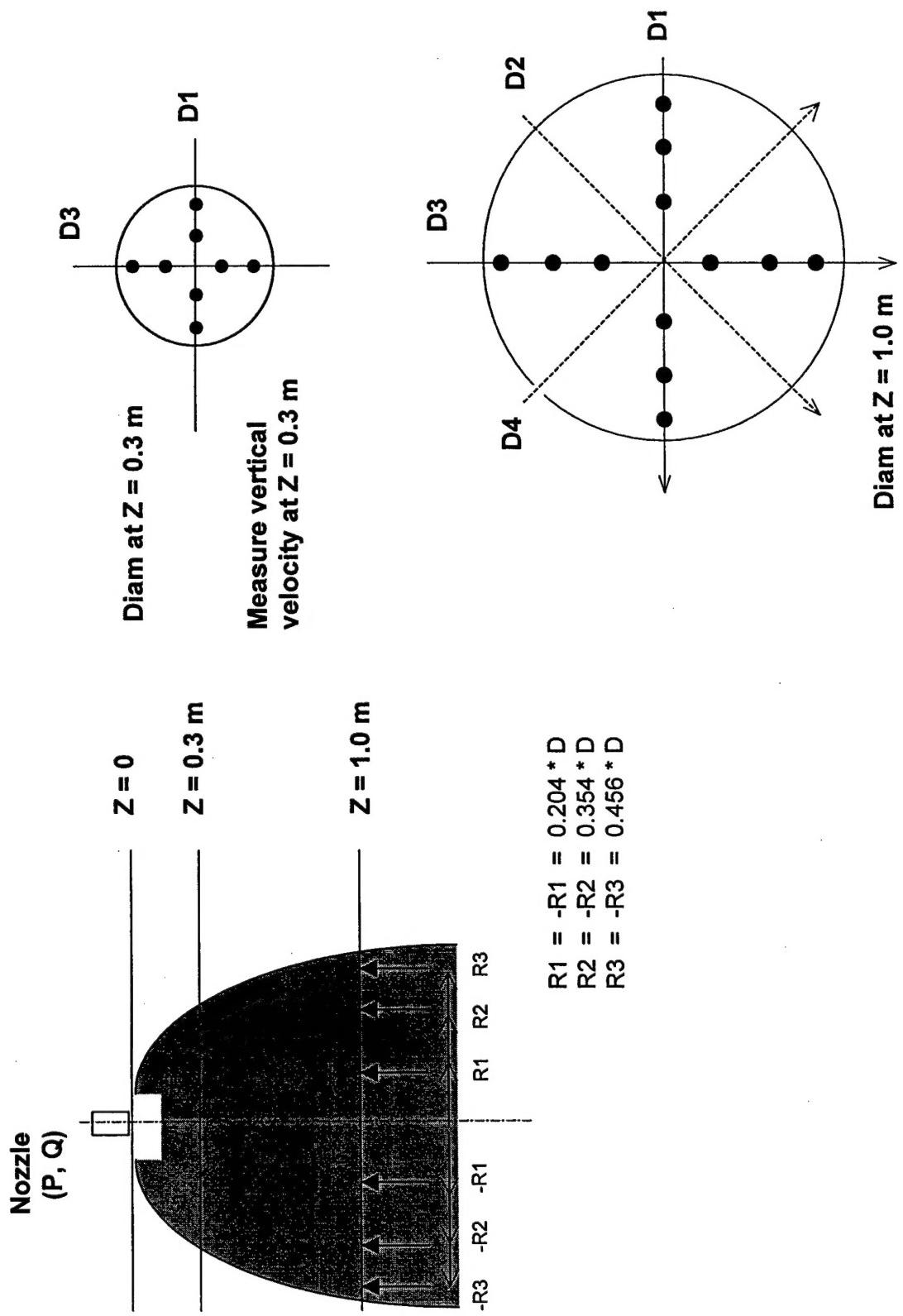


Fig. 2 – Locations for measurement of Drop Size Distribution (DSD) and vertical velocity

The nozzle was operated at its design pressure for enough time to collect a measurable quantity of water in the collectors. The duration of discharge was recorded, and the mass of water in each collector was measured.

$$V_i'' = \frac{W_i \times 10^{-3}}{A_i \times t} \quad (1)$$

where V_i'' = flux density at position I , L/min/m²,

W_i = weight of water in collector at position I , grams,

A_i = area of collector opening, m², and

t = duration of flow, minutes.

2.2.3 Spray Velocity

Measurement of 'spray velocity' involved measuring the velocity of the combined mass of water droplets plus entrained air. No attempt was made to measure the velocities of individual water droplets, some of which have velocities greater than the average velocity of the entrained air. This measurement has value for comparing the ability of different nozzles to entrain air (vitiated fire gas) near ceiling level and push it down toward the floor, where it contributes to suppressing fire.

The velocity measurement was taken by placing a vane anemometer into the spray, facing upward. The speed of rotation of the anemometer is a function of the vertical air velocity. Water droplets striking the vane may either cause a slight acceleration, or retard the rotation by adding mass in the form of water adhering to the surfaces of the vanes. This device produces an empirical measure of spray velocity useful for comparing how different nozzles affect compartment conditions.

The vane anemometer utilizes a 4 pole magnet rotating past a hall-effect switch. The magnet is housed in a fan blade which rotates a 3 mm spindle in a pair of small sealed roller bearings. The square wave pulse has a frequency which is proportional to the air stream velocity. The frequency pulse is converted to a variable output voltage using tachometer circuitry [7]. The pulse rate is proportional to the velocity of the air stream. The calibrated best-fit curve for the device is as follows:

$$V = 14.479 * \text{Rdg} + 0.516$$

V = average spray vertical velocity, m/s

Rdg = Recorded Voltage reading, volts

The vane anemometer readings are not accurate for air stream velocities less than about 0.6 m/s.

2.2.4 Drop Size Distributions

A Malvern 2600 forward-light-scattering particle size anemometer was used to measure drop size distributions (DSDs) of the selected nozzles. As drop size distributions vary radically at different locations in a spray, no single reading can be statistically representative of the entire spray. Also, spray drop size characteristics change continuously as the distance from the nozzle increases. In this test program, drop size distributions were measured at several points on a plane 1.0 m vertically below each nozzle, where the spray cone is fully developed, as recommended in the appendix to NFPA 750 [8].

The selection of the number and position of measurement points was based on a standardized methodology used for measuring sprays used in characterizing sprays for environmental gas-scrubbing equipment [9]. This methodology has been proposed for adoption by NFPA 750 [9]. Traverses consisting of 6 readings are made in two directions across the spray diameter, for a total of 12 independent readings, as illustrated in Figure 2. In some cases, four traverses may be required for a total of 24 readings. For a spray with a single peak in its flux density profile, two 6-point traverses were sufficient. For a spray with irregularities in the flux distribution, four 6-point traverses (total 24 points) were used. The radial distance from the center of the spray cone to the point of measurement was determined so that each point represented an equal proportion of the entire cross-sectional area of the spray cone. A separate measurement was taken of the flux density distribution within that spray cone, at a distance of 1.0 m below the nozzle. It is normal for there to be significant variations in flux density distribution within a spray cone. DSD readings from areas of high flux density are deemed to represent a larger proportion of the mass of the spray than readings from areas of low flux density. Thus, the flux density at the points of DSD measurement can be used to ‘weight’ the individual DSD readings. In this way, a “weighted average” drop size distribution, statistically representative of the spray, can be generated.

The equation for doing the weighted average cumulative percent volume is as follows:

$$WR_k = \frac{\sum_i (R_{i,k} \times A_i \times V_i'')}{\sum_i A_i \times V_i''} \quad (2)$$

where WR_k = weighted cumulative volume percent reading for drop sizes equal to and less than d_k ,

$R_{i,k}$ = cumulative volume percent reading for drop sizes equal to and less than d_k at Location I,

- A_i = local area centered at Location I in which the drop size distribution can be closely represented by $R_{i,k}$. (A_i = Total Area of Cone/No. of traverse points), and
- V_i'' = the water flux density in L/min/m² at Location I.

The resulting ‘weighted average cumulative percent volume distribution curve’ allows comparison of the average particle size distribution of different nozzles, by eliminating the wide fluctuations that appear in individual readings taken within a spray. Although individual readings may be skewed by a few larger diameter drops, the weighting process described here results in a statistically stabilized representation of the drop size distribution characteristic of the nozzle. The weighted distribution can also be used as input to a Computational Fluid Dynamics model of water mist and fire interaction. The measurement procedure was as follows:

- (a) Collect data for the flux density distribution, from which the diameter of the spray cone at 1.0 m from the nozzle was determined. From plots of the density profiles, the effective diameter (D) of the spray cone was taken as the distance between points at which the flux density was less than 0.05 L/min/m².
- (b) Calculate the positions for measuring drop size distribution along each axis of the spray as radial distance from the center axis of the spray, R1, R2 and R3: [8]

$$R1 = 0.204 * D$$

$$R2 = 0.354 * D$$

$$R3 = 0.456 * D$$

The positions determined by these proportions represent the centroids of segments of equal area.

- (c) The Malvern 2600 Particle Size Anemometer was set up within a plexiglass protective structure. Chambers protecting the instrument from water were under a slight positive air pressure, to minimize accumulation of mist on the receiving lens. A collimating tube was used to protect the laser beam from spray, except for the last 100 mm before the receiving lens, which was open to the spray. The measurement volume was approximately 8 mm in diameter by 100 mm. The lens range was 11.6 to 1128 microns, mounted on the “long bed” [10].
- (d) The orientation of the nozzle with respect to arms or orifice positions was noted; the Malvern was moved along each axis, D1, D3, (in some cases also D2 & D4) to the positions R1, R2, R3, on the centerline of the spray (CL), then along the axis to -R1, -R2 and -R3, for a total traverse of six readings per diameter. The nozzle was rotated 90 degrees, and a second traverse made, representing D3. Malvern data was rejected if the “% obscuration” exceeded 0.30%, or if the Upper bin size cumulative value was not more than 99 percent of the volume of the spray

- (e) The flux density and drop size distribution data for each position were tabulated in Sigma Plot (v4). The weighting algorithm described above (equation 2) was applied, and a single, statistically averaged curve for cumulative percent volume was generated and plotted.

2.3 Spray Characterization Results

Table 1 tabulates the measurements for each nozzle used in the fire testing, for comparison. Figure 3 compares the weighted cumulative percent volume distribution versus diameter curves for the four nozzles used for fire testing.

Table 1. Comparison of Spray Characteristics of Selected Water Mist Nozzles

	AM10	K1214	MF-11	NAVY
Operating Pressure, bar	12.0	13.1	70.0	72.0
Nominal Discharge Rate, L/min	12.1	4.7	15.9	14.4
Measured Discharge Rate per Nozzle, L/min	12.1	5.3	13.0	15.3
Manufacturer's "K" factor, L/min/bar ^{1/2}	3.5	1.3	1.9	1.7
Averaged "K" factor, L/min/bar ^{1/2}	3.5	1.5	1.6 – 1.9 *	1.9
"Power Coefficient" [(Q x H)/600], kW	0.2	0.1	1.5	1.8
Effective Cone Diameter @ 1 m, m	1.6	1.5	1.8	1.7
Peak flux density, L/min/m ²	11.0	9.0	17.5	14.0
Nominal average cone density, L/min/m ²	6.0	4.7	5.4	7.2
Weighted Average D _{v0.9} , microns	590	360	190	150
Weighted Average D _{v0.5} , microns	310	230	110	125
Weighted Average D _{v0.1} , microns	120	90	40	40
Spray velocity at 0.3 m below nozzle, m/s, Average over width	4.5 / 0.2 m	< 1.5 / 0.2 m	14.0 / 0.2 m	4.8 / 0.2 m
Spray velocity at 1.0 m below nozzle, m/s, Average over width	4.0 / 0.2 m	< 1.0 0.2 m	5.3 / 0.2 m	3.8 / 0.2 m

Notes:

* The K factor of 1.88 (1.9) for the Marioff nozzle (MF11) is the result of a regression on Q versus Sqrt(P) data shown in Figure 1-C.1. Individual readings taken around 70 bar consistently showed a K factor of 1.6.

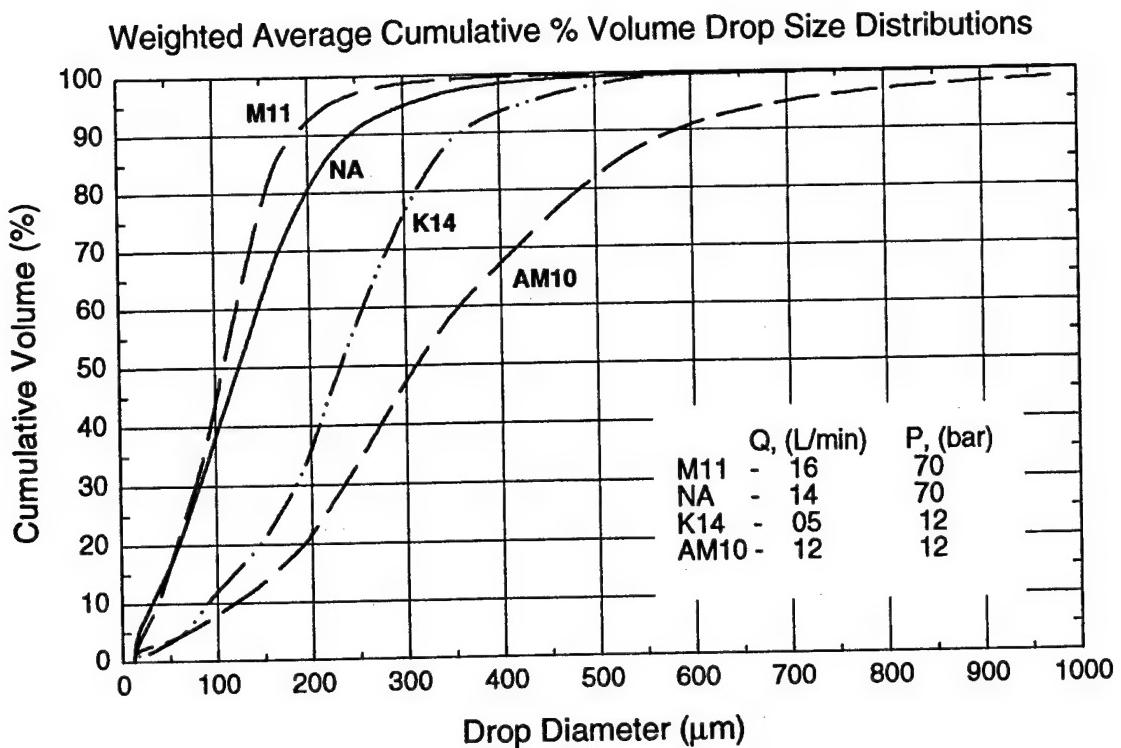


Fig. 3 – Weighted average drop size distributions, measured 1 m below nozzles

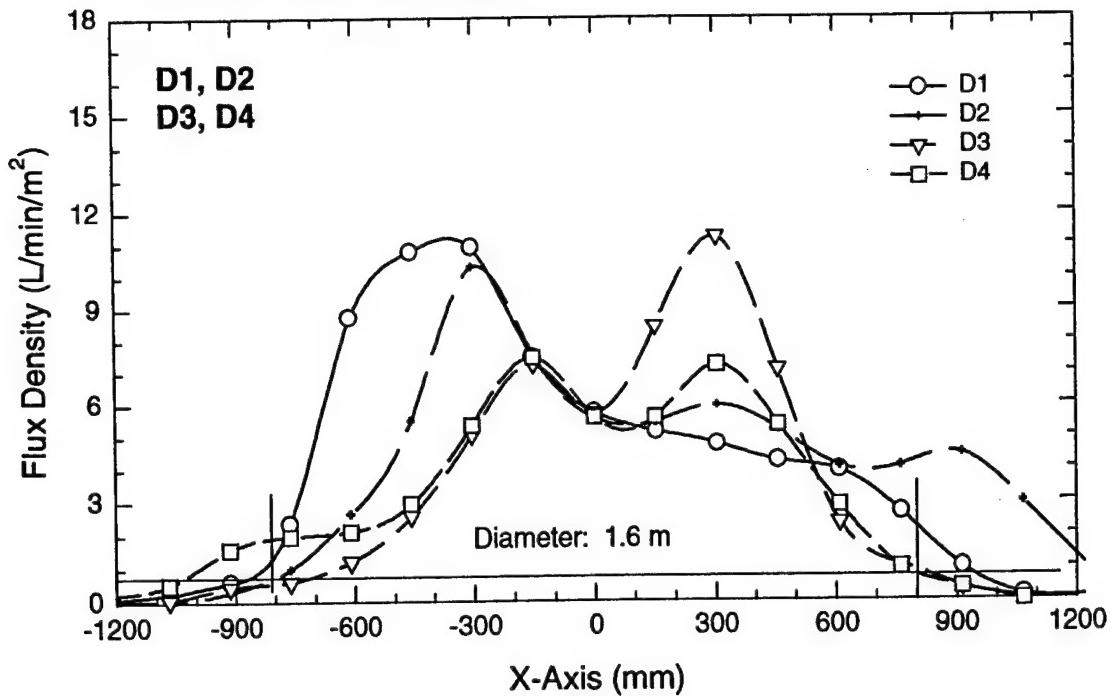
Figure 4 compares flux density distributions measured 1 m below an impingement nozzle and the same distance below a high pressure jet nozzle. Figure 5 compares velocity profiles 1.0 m and 0.3 m below the same two nozzles.

2.4 Discussion of Spray Characterization Results

Spray characterization (Task 1) results quantify specific aspects of water mist spray characteristics for use in analysis of the performance of those nozzles in fire suppression systems. The following observations are highlighted:

- (1) The low pressure nozzles deposit most of their mass within the spray cone diameter. Cone diameters at 1.0 m below the nozzle are typically under 1.5 m. If the hypothesis that water spray has to be deposited uniformly over a floor area were true, nozzles would have to be spaced the same distance apart as the effective cone diameter. This would lead to close nozzle spacing and a large number of nozzles would be required to protect a space. As will be discussed in the next section, the fire testing illustrated that the water mist system does not have to be designed on the basis of ‘overlapping-spray-cones’ to achieve flashover suppression.
- (2) The “nominal average flux density” is commonly used as a design parameter for water based suppression systems. The concept carries an assumption that suppression performance can be related to an averaged distribution in the compartment. The flux density profiles show that peak values may be several times greater than averaged values over the cone width. The relationship between flux and suppression effectiveness may depend more on the irregularity in the spray than on its uniformity.
- (3) Velocities of entrained air and water spray (averaged over a 0.20 m diameter distance of the spray) varies greatly over short distances. For example, the MF-11 nozzle goes from more than 14 m/s to 1 m/s in less than half a meter. The regions of high and low velocity correspond to the regions of high or low flux density, essentially governed by the ‘spray fingers’ of the pressure jet nozzles. Multi-orifice nozzles such as the Navy and Marioff nozzles, manifest regions of high and low velocity within the spray cone. In contrast, an impingement nozzle such as Grinnell AM10, will have a single peak velocity in the center, diminishing toward the edge of the spray cone. It is hypothesized that the ability of the water mist nozzle to entrain vitiated gases and mix them in a compartment is related to the measurable degree of unevenness in the velocity profile of a water spray.

AM10 Flux Density Distribution



Marioff 4S 1MC 8MB 1100 Flux Density Distribution

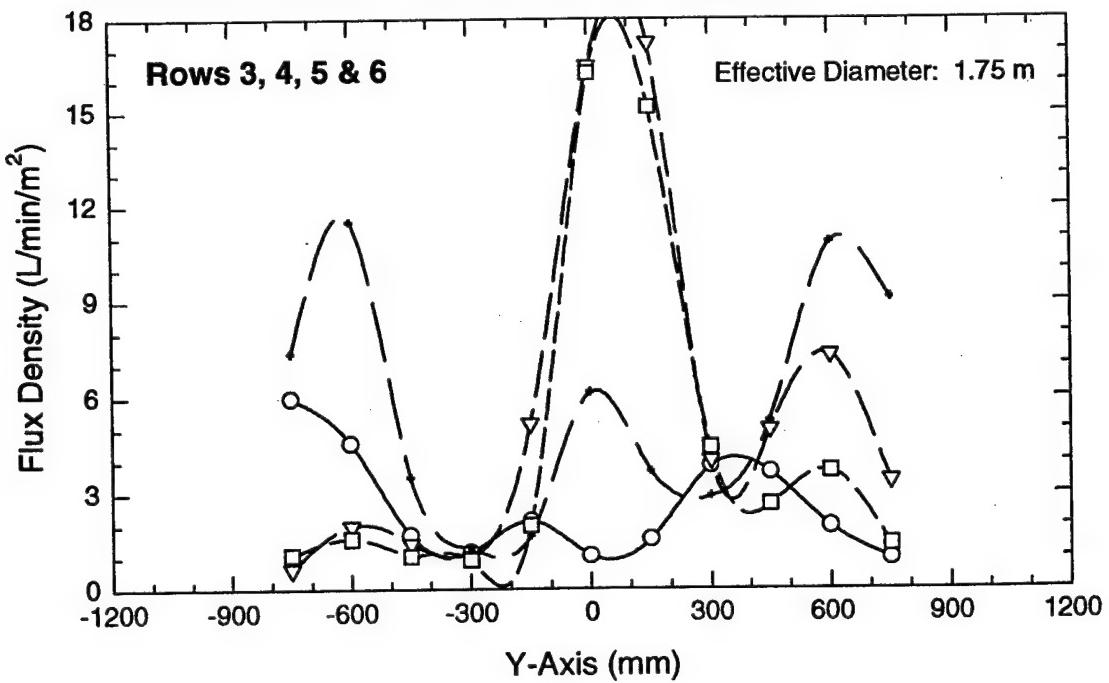


Fig. 4 – Comparison of flux density profiles for AM10 at 12 bar and a Marioff 4S 1MC 8MB 1100 at 70 bar, measured 1.0 m below nozzle

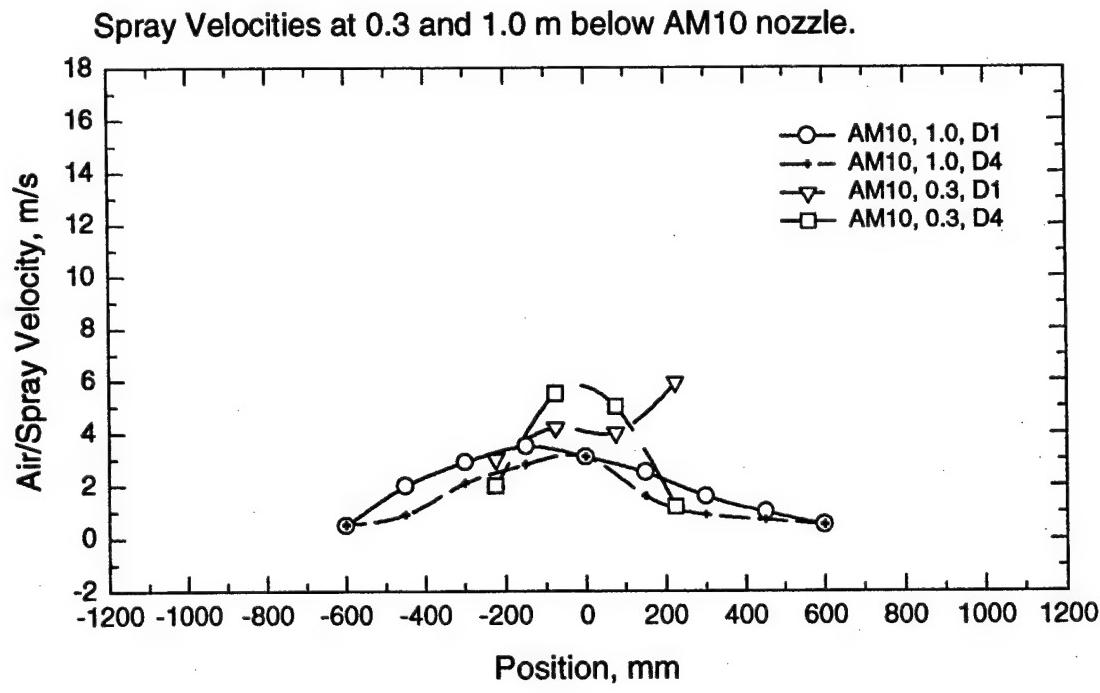
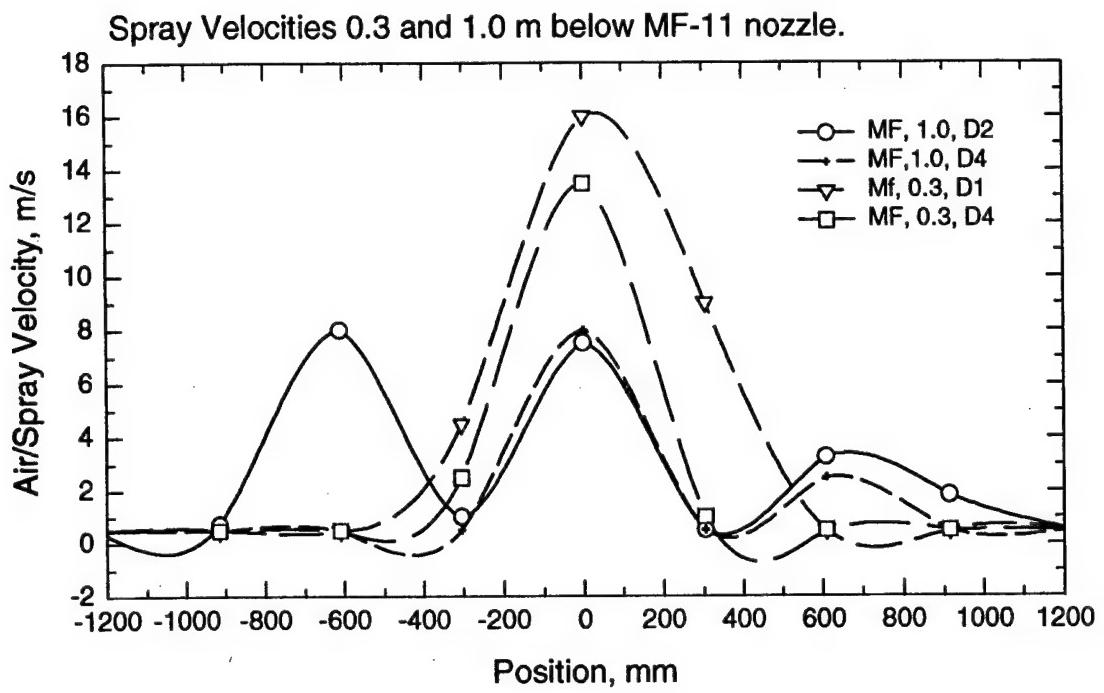


Fig. 5 – Comparison of average air/spray velocities below a low pressure Aquamist AM10 nozzle and a Marioff 4S 1MC 8MB 1100 high pressure nozzle

- (4) The drop size distributions follow a logical sequence from ‘coarse’ for low-pressure impingement nozzles ($D_{v0.9} = 590 \mu\text{m}$), to ‘fine’ for high-pressure jet nozzles ($D_{v0.9} = 150 \mu\text{m}$). It is noteworthy that the high pressure nozzles achieve such a high fraction of fine particles at flow rates equal to or greater than the low-pressure nozzles. The cost of that achievement is the energy required to operate a system at higher pressures.
- (5) Table 1 provides quantified values for certain spray characteristics associated with the selected water mist nozzles. This data is a first step toward identifying the characteristics of water mist that can be used as design criteria. Relationships between measurable spray characteristics and performance will be tested through examination of the Task 2 fire test results.

3.0 FIRE TESTING FOR FLASHOVER SUPPRESSION

3.1 Test Structure

Full-scale fire tests were conducted in a 6.7 m x 3.7 m x 2.4 m high (60 m^3) test room constructed under the hood of the Calorimetry Building at the Chesapeake Bay Detachment test site (CBD). The Task 2 Test Room consisted of a 2 x 4 wood frame covered on the inside walls and ceiling with Type X gypsum board. A 0.56 m x 1.68 m opening in the north wall of the room represented a typical “Navy door” in a berthing space. For the first set of tests, this ‘Navy door’ was the primary source of ventilation air to support combustion in the compartment (apart from leakage). Ventilation air from the attached corridor had to pass over a 0.30 m high sill to enter the room. All smoke left the compartment via the Navy door, then passed through the corridor before escaping into the building and being captured by the building hood/fan system. As the fire testing progressed, a second ‘Navy door’ opening was introduced in the south wall in order to examine the effects of increased ventilation on the nozzle performance. A large door in the east wall of the compartment was used for access for setting up the fuel packages and igniting the fires. This door was also used in several tests to simulate a major change in the availability of ventilation air, as with opening of a large hatch, or breach of a compartment. The test room and its instrumentation are illustrated in Figures 6 through 12.

3.2 Instrumentation

The instrumentation in the test facility, shown in Figures 7 to 12, consisted of the following:

- (1) Thermocouple trees (TRs) consisting of 8 thermocouples (TCs) each, spaced 0.3 m apart from the ceiling down to 0.3 m above the floor. The locations of TR-1 through TR-6 are shown in Figure 7. TCs were type K, chromel alumel

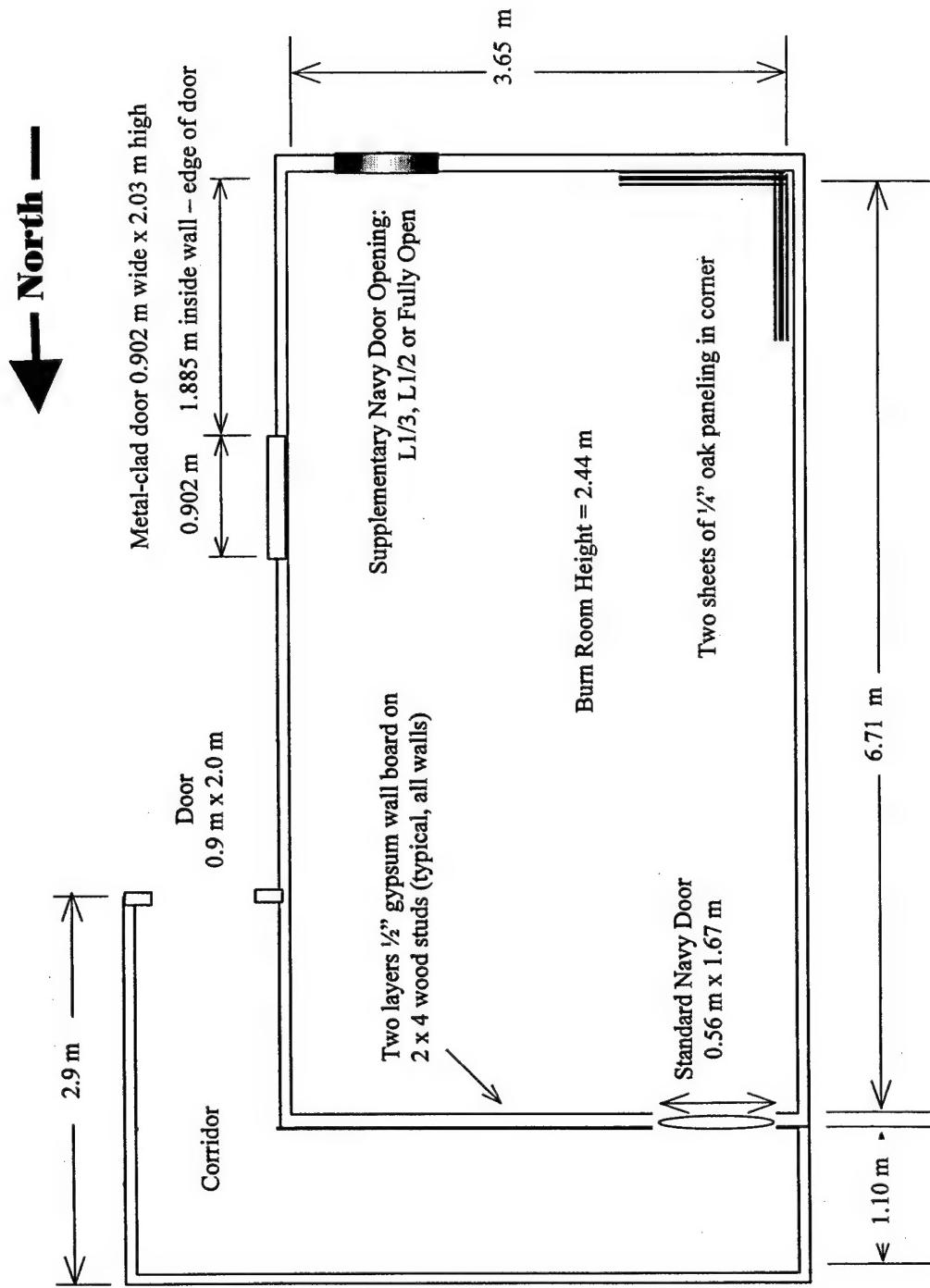


Fig. 6 - Test room – general arrangement and dimensions

— North —

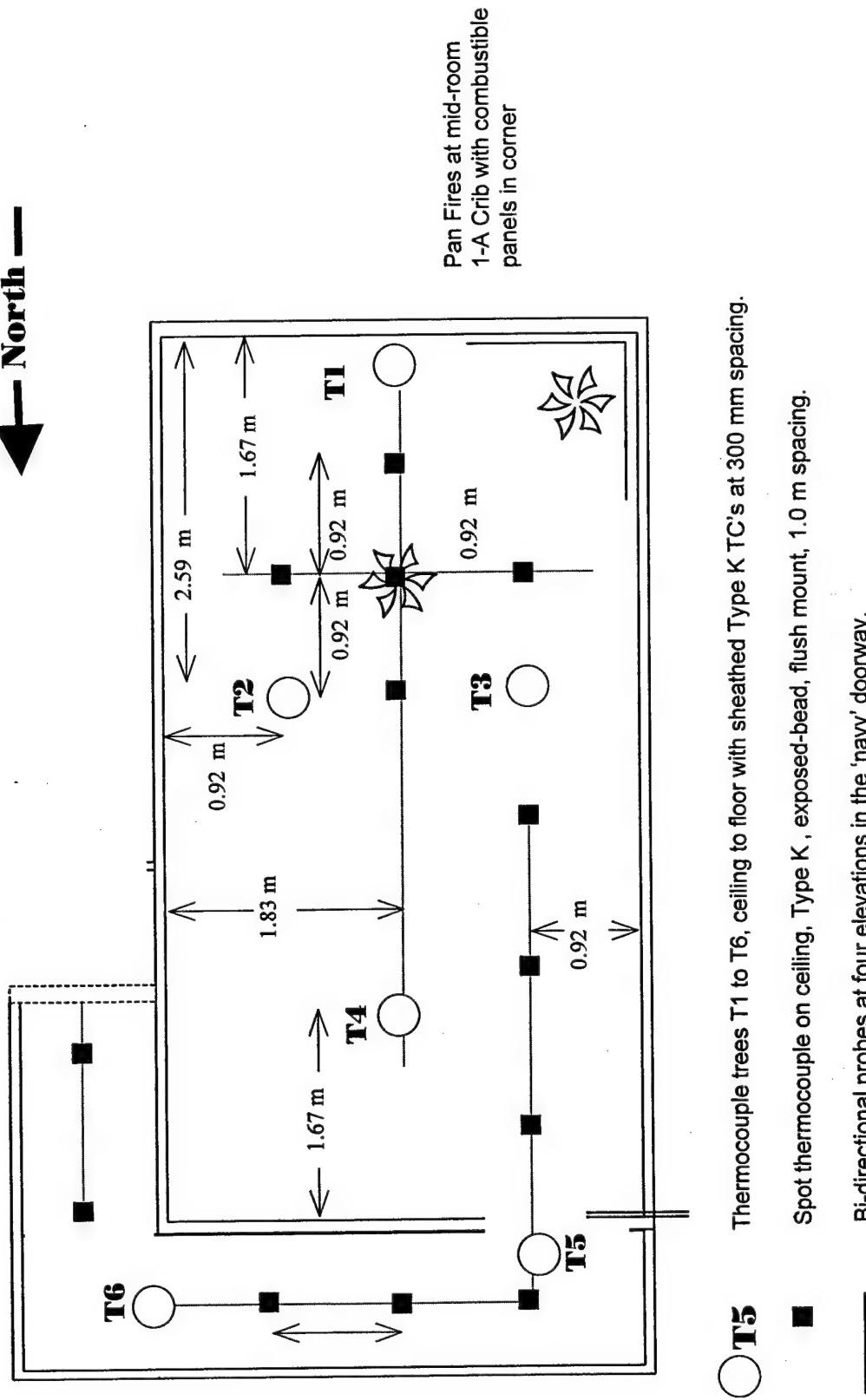
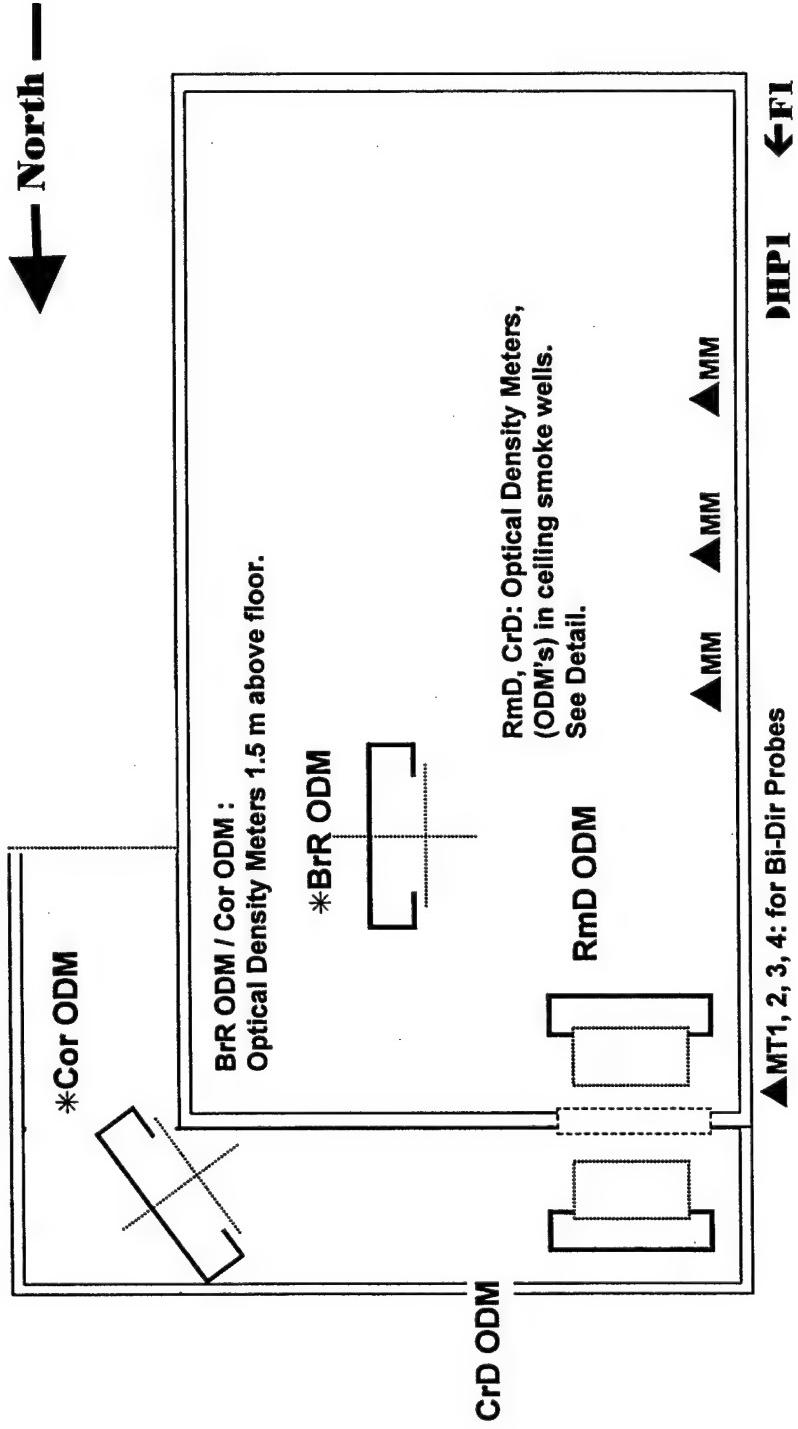


Fig. 7 - Test room – thermocouple locations



- HP1, 2** High pressure transducer, 0 – 200 bar, Omega model PX725-3KGI
- ◀F1** Flow meter(s), high range: two @ 1 - 36 L/min each, (Sponsler 1/2 Turbine type)
- ▲MM** Micro-manometers, data & digital readout, adjustable range, 0 - 500 Pa
- ▲MT** Micro-transducers, for bi-directional probes - 4 in doorway 0 - 500 Pa

Fig. 8 – Test room – instrumentation details

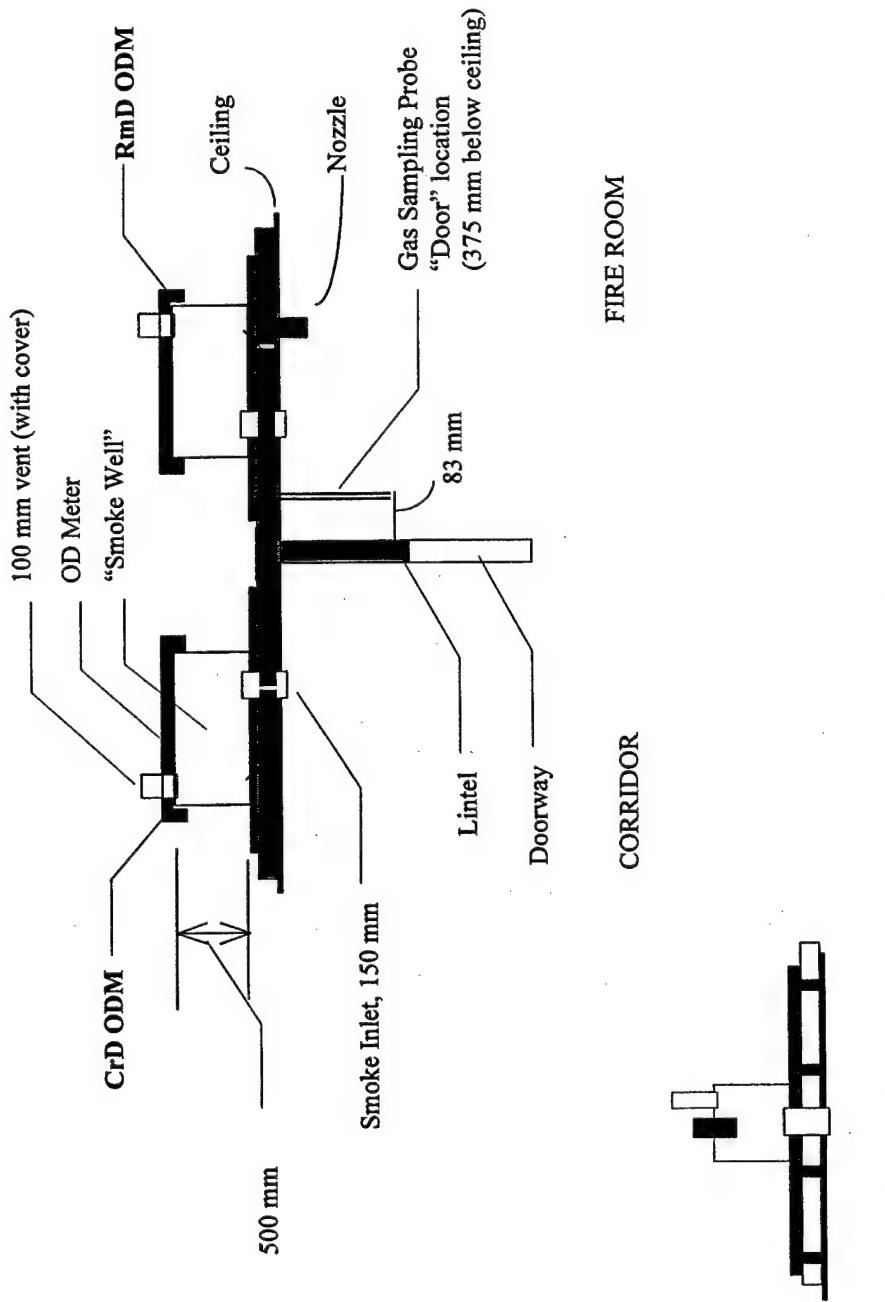


Fig. 9 – Test room – smoke-well details

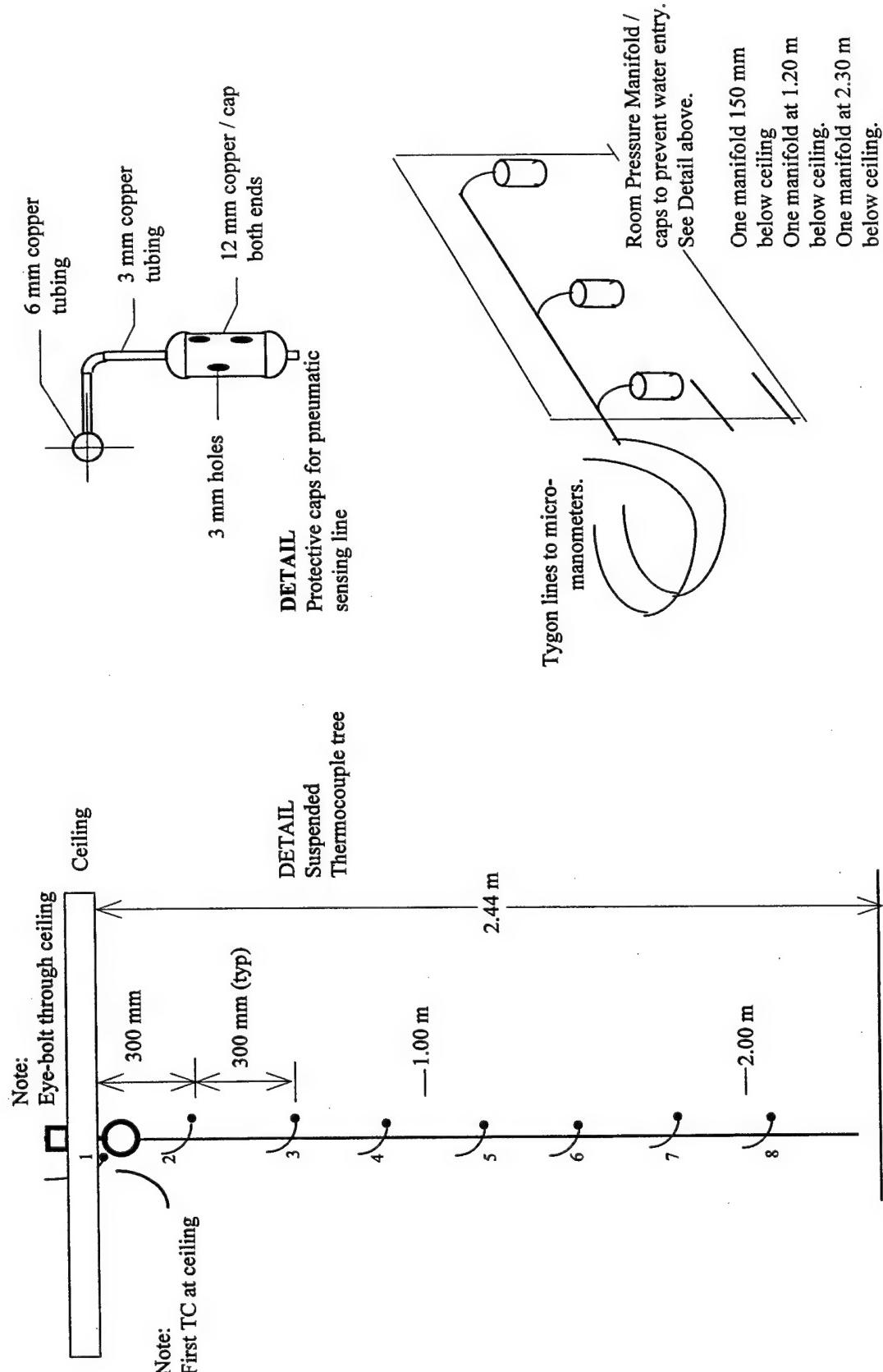


Fig. 10 – Test room – thermocouple tree and room pressure details

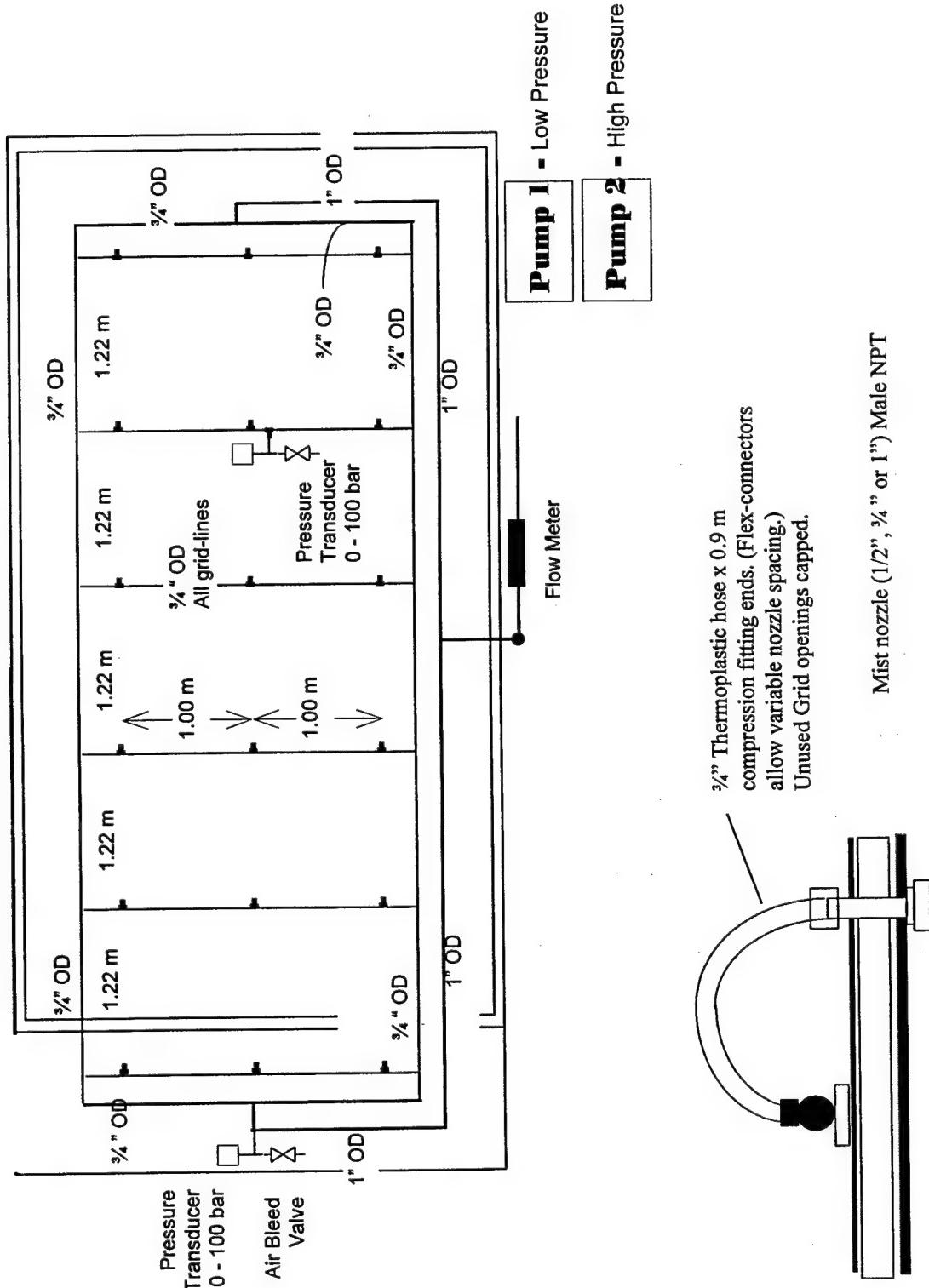


Fig. 11 - Test room – water supply and piping layout

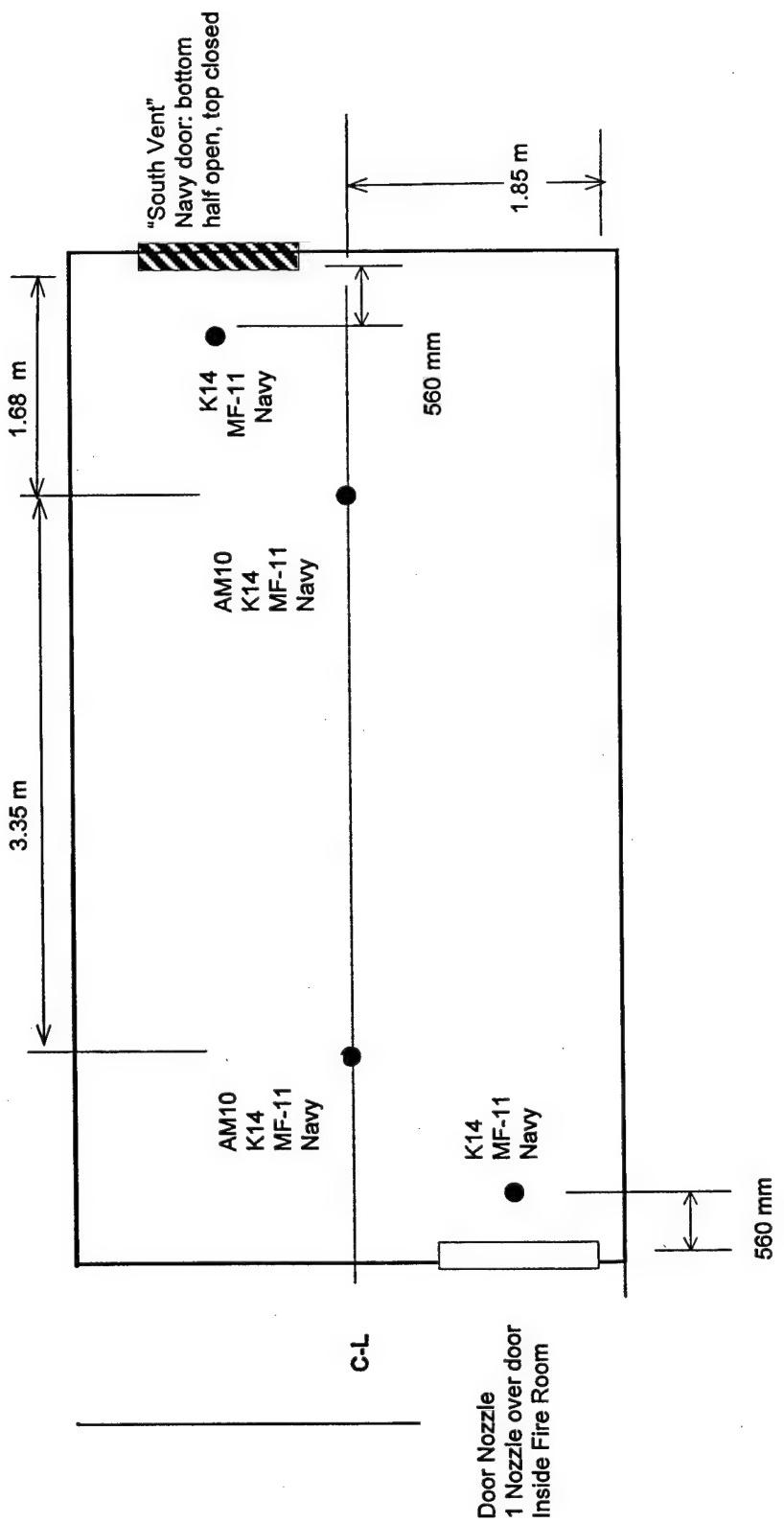


Fig. 12 – Test room – typical nozzle locations

thermocouple wire. Most TR TCs were sheathed. Ceiling mounted TCs were exposed bead;

- (2) TCs mounted flush with the ceiling to measure temperature changes over the ceiling of the fire compartment and adjacent corridor;
- (3) Bi-directional probes in the north Navy door to measure air and smoke movement in and out of the compartment;
- (4) Pressure transducers to measure the buoyancy-induced pressure difference across the wall separating the burn room from the surrounding laboratory area;
- (5) Four optical density meters (ODMs) to measure the opacity of smoke. Two were installed at eye-level, one in the burn room and one outside the burn room in the corridor. Two more were mounted on ceiling mounted 'smoke wells.' Smoke from the ceiling of the burn room or the corridor was diverted through a dedicated smoke well. The intention of the smoke-well arrangement was to measure differences in the opacity of smoke before and after mist application, without the complicating factors such as non-repeatable changes in height of the neutral plane in the compartment, or different degrees of stirring or mixing of smoke, which affected conditions at eye-level;
- (6) Gas analysis was conducted of gases sampled from inside the burn room. Readings of O₂, CO₂ and CO were taken from a single gas-sampling line. The location of the sampling point was varied throughout the test program. In most tests, gases were sampled from 0.46 m below the ceiling at the lintel of the 'Navy door' outlet from the room. In other tests, gas was sampled from mid-height in the room near TR-4. A few tests were run with gas sampling near floor level, 0.3 m above the floor at TR-2, to determine whether vitiated gases were entrained below the neutral plane in the air-stream feeding the fire;
- (7) A hood and fan system captured smoke from the fire room. Gas temperatures and velocity in the exhaust duct, as well as concentrations of O₂, CO₂ and CO were measured; and
- (8) Flow and pressure measurements were made on the water distribution system using the same Sponsler flow meters, and Omega pressure transducers, as were used for Task 1. Water pressure readings were made on the riser and at two points on the ceiling tubing grid, to ensure that flow was evenly distributed throughout the supply piping, and hence that all nozzles were operating at the same pressure.

Data acquisition was organized using Labtech Notebook on the field PC at CBD. Over 100 channels of data were collected.

3.3 Fire Scenarios

The test series intended to examine flashover suppression, not extinguishment of fires. The fire scenarios were therefore designed on the following bases:

- (a) the fire would not be immediately extinguished by the mist due to shielding or the manner of application of mist;
- (b) that fire would be suppressed by the mist as evidenced through reduction in HRR;
- (c) heat would continue to be generated at a reduced rate throughout the application of mist;
- (d) if not suppressed, the fire would bring the compartment to flashover conditions.

The test fires had to satisfy the following additional conditions:

1. The fire should be as large as could be supported by the natural ventilation through the single Navy door in the north wall under unsuppressed conditions;
2. The fire should not be so large that it self extinguished by consuming all of the available oxygen;
3. The size of fuel package should be large enough that the fire could bring the compartment to flashover before all of the fuel was consumed;
4. The fuel package should be such that differences in burning rate or fire growth caused by the water mist systems could be visually evident, e.g., as extent of fire spread on a surface or extent of char, so that differences in performance could be noted.

Two types of fire sources were used in the test series – a square pan with heptane fuel and a small wood crib with combustible wood panels situated in a corner. The heptane pan fire provided information on spray cooling of large flames and extinguishment through oxygen reduction. Unsuppressed, the 8.0 L of heptane was consumed before the compartment became hot enough to meet a definition of flashover (Test T14K0A1). It did not satisfy conditions #3 and #4, therefore, although it did satisfy conditions a) through c), and #1 and #2.

The wood crib with combustible wall panels scenario satisfied all of the conditions described. Unsuppressed, it was able to bring the compartment to flashover; the burning rate,

hence heat release rate of the wood char responded to changes in water mist application; there was enough fuel to allow "steady-state" conditions to develop in the compartment; and the amount of fuel physically consumed could be measured after the test were completed.

The "Pan A/8" fuel arrangement consisted of a 0.7 m x 0.7 m x 0.15 m high steel pan with 8.0 L of heptane. This pan was placed under a steel frame which supported a 1.2 m x 1.2 m flat steel plate of 6 mm thickness. The underside of the steel plate was 0.60 m above the surface of the heptane placed in the pan. The purpose of having the steel plate was to 'shield' the fuel surface from direct interaction with the water mist. Thus, extinguishment of the pool fire was hindered by the obstruction. The steel obstruction also reflected more heat to the fuel surface than would have been the case with an unobstructed pan fire. It is believed that the obstruction increased the burning rate of the fuel as well as hindered the ability of the mist to extinguish it. The heat release rate of 8.0 L of heptane (without the steel plate) was calculated to be 690 kW. It is estimated that the reflected heat trapped under the steel plate accelerated the burning rate, so that the peak HRR exceeded 700 kW. It took very close to 4 minutes to consume the 8 Liters of heptane with the steel covering plate in place.

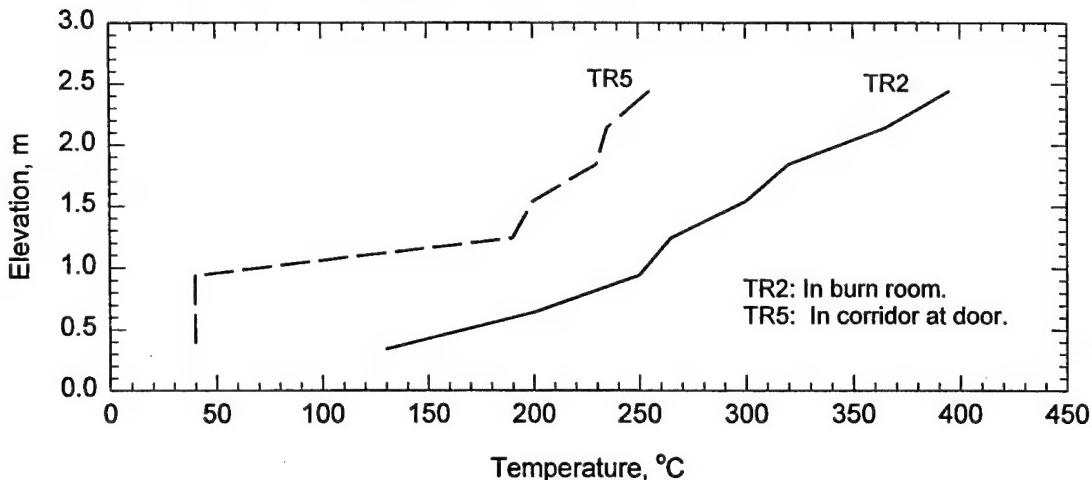
The UL-722 - 1-A wood-crib was constructed of ten layers of five 38 mm x 38 mm x 508 mm long oven-dried pine sticks, with overall dimensions 508 mm x 508 mm x 380 mm high. It was placed on 38 mm brick supports in the southwest corner of the room with approximately 12 mm between the edge of the crib and the wall surfaces. The south and west walls of the corner were lined with 1.2 m x 2.4 m x 3 mm (1/8 in.) Georgia Pacific medium density fiberboard wall paneling mounted on 20 mm fir strapping. The crib was ignited using 100 mL of heptane in a 100 mm x 100 mm pan placed between the supporting bricks under the center of the crib.

Two tests (T3-A10-- and T8-A10--) involved a UL 4-A crib consisting of 15 layers of 8 sticks. Fire growth in this large crib was too rapid for the ventilation-limited compartment. The crib was quickly extinguished as soon as the mist was turned on.

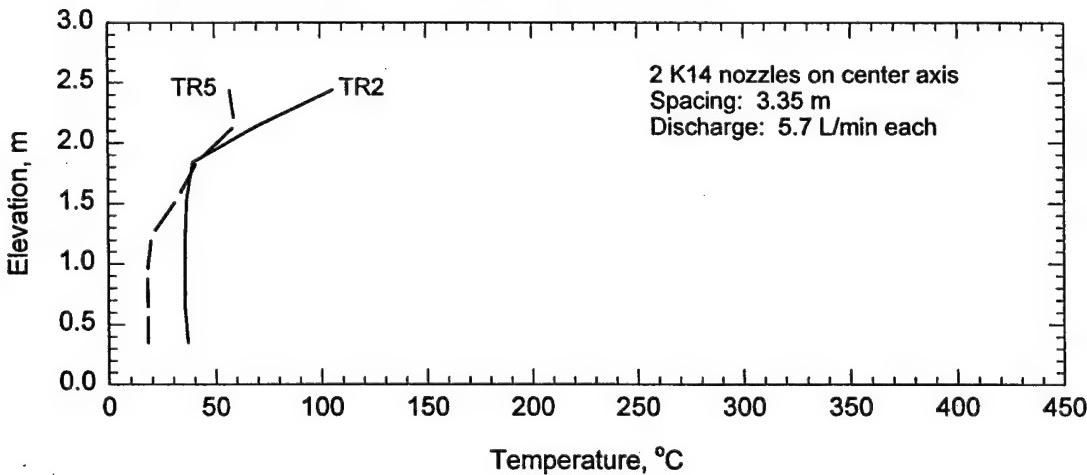
3.4 Evaluating "Flashover Suppression"

"Flashover" is defined by various documents as a condition in which all parts of the compartment are hot enough to cause ignition of all combustibles [3]. Some sources suggest that 500°C defines the beginning of flashover; others refer to temperatures of 600°C. The unsuppressed wood-crib fire brought the compartment to the point at which cardboard target boxes ignited; the neutral plane was within 0.5 m of the floor. Figure 13 shows a temperature profile in the compartment at the peak of the fire. Except immediately over the fire, ceiling temperatures were below 400°C, and the temperature at mid-height in the room was below 275°C. Based on temperature alone, this condition would not meet the definition of 'flashover' in NFPA 555 [3]. Given that the unsuppressed crib fire was hot enough to ignite the target boxes, the temperature profile in Figure 13 represents the beginning of flashover. If more fuel had been

Test T9 N0 3C: Unsuppressed Crib Fire.



Test T18 K14 C3: Suppressed Wood Crib, $t = 600$ s



Test T26 K14 C3: Suppressed Wood Crib Fire, $t = 720$ s.

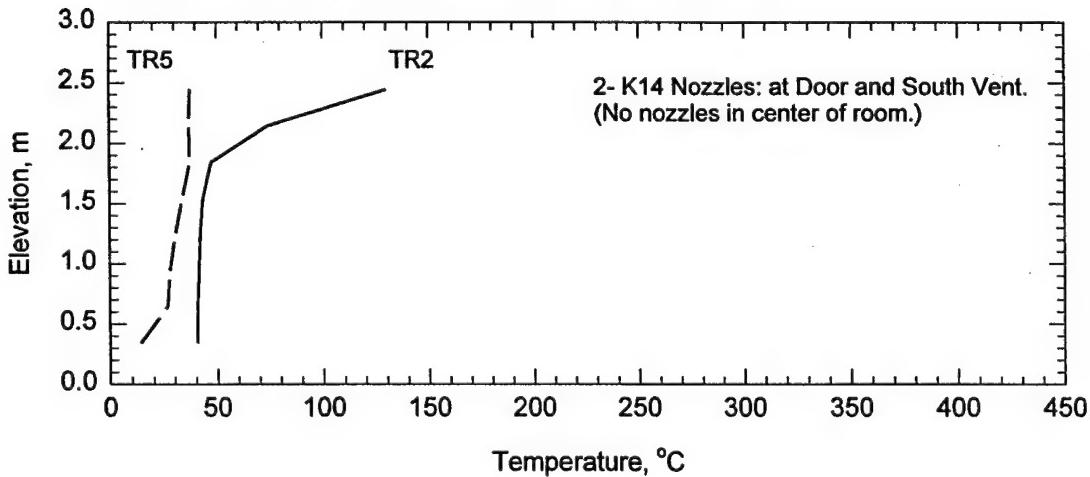


Fig. 13 – Temperature profiles in room and in corridor, > 1 minute duration

present, the compartment would have progressed to true flashover. For the purposes of this test series, "flashover control" is defined in terms of the ability of water mist to prevent ceiling temperatures in the compartment from exceeding 400°C.

There are other indicators of conditions in the compartment which reflect on the ability of the mist to prevent flashover. The maximum buoyancy pressure generated by the unsuppressed wood crib fire, Test T9N03C, was close to 10 Pa. Tests in which the fire was controlled by the water mist typically showed Delta P values at ceiling level less than 2 Pa. As the value of Delta P at the ceiling is a manometer reading averaged across the compartment's west wall (see Figure 10), it reflects the room environment better than individual thermocouple readings, which may differ greatly depending on their distance from the fire. The Delta P reading reflects the compartment conditions with less variability than individual temperature readings.

3.5 Test Matrix

Table 2 is a matrix of questions and variables which were investigated as part of the full-scale testing. Test conditions were varied in order to 'answer' specific questions about the effect of changing certain parameters or conditions. Not all tests were conducted for all nozzles. For example, questions relating to the effects of cycling the water spray (water on/off) were investigated during the Aquamist testing. A supplementary measurement was obtained during one Marioff nozzle test, when the water was turned off because the fire appeared to have been extinguished, but was not. Since the effect of cycling sprays on Class A fires was evident from the results of the two tests conducted, it was not deemed necessary to repeat the cycling experiment with each of the other nozzles. Similarly, it was evident that the wood crib corner fire tests provided more useful information about compartment cooling, steady-state conditions, smoke scrubbing, cycling, etc. than the pan fires. Therefore, although pan fires were investigated thoroughly for the first 3 nozzles tested, later tests concentrated on wood crib fires. The matrix in Table 2 indicates the types of variations that were performed to investigate different questions of interest.

An Index of Fire Tests is presented as Table 3. It summarizes information about the conditions of each test, specifically the type and location of fuel package, type, number and location of nozzles, operating pressure, ventilation conditions, pre-burn time.

Table 2. Matrix of Questions of Interest and Choices of Variable in the Fire Test Program

Question of Interest		Action or Variation		
		1	2	3
A	Type of fuel package	Heptane Pan Fire, shielded	4-A Wood Crib, shielded, mid room	1-A Wood Crib + Panels not shielded
B	Effect of fire location relative to nozzle location	Position 1 – Under one nozzle	Position 2 - between two nozzles	Corner – beyond reach of spray cone on CL.
C	Spacing & Number of nozzles distributed in room	2 Rows, 5 Nozzles, stagger spacing	1 Row, 2 – nozzles on CL, widely spaced.	1 nozzle, mid room, CL
D	Spray characteristics, high /low pressure; drop size distribution: coarse/fine...	Low Pressure/Coarse: Aquamist AM10 Kidde ESK 1214	High Pressure/Fine: Marloff MF-11 Navy	Cone angle: MF 120° Navy (120°)
E	Using nozzles to block ventilation at doorway.	2 Nozzles CL, plus 1 nozzle at door	1 nozzle at door only	1 nozzle at door plus 1 nozzle at Vent.
F	Effect of changing ventilation.	One ‘navy door’	Navy door plus additional south Vent	Breach or Entry, side door opened.
G	Effect of cycling water spray...	Flow stopped for xx s, resumed, repeated	Fire assumed to be out, water shut off	
H	Effect of Mist on ODM readings in smoke wells....	Heptane: Unsuppressed Wood: Unsuppressed	Nozzles on CL only. Nozzles on CL only.	Nozzles over Door Nozzles over Door

Table 3. Full-scale Test Index (Volume II contains Appendix 2A through 2E)

Date 1998	Test #	# Nozzles & Where	System Press. (bar)	Fuel Config.	Position in Room	North Door	South Door	Preburn Time (s)	Exting. Time (min:sec)	Notes
Appendix 2-A										
Grinnell Aquamist	AM10									
May 20	T1A10B2	5-AM10-ST	13	4A crib	P1	Open	No	180	Rapid	<i>Compartment is</i>
May 20	T2A10A2	5-AM10-ST	13	PanA/8	P1	Open	No	240	Rapid	<i>Ventilation Limited.</i>
May 21	T3A10B2	2-AM10-CL	13	4A Crib	P1	Open	No	240	< 1:30	
May 21	T4A10A2	2-AM10-CL	13	PanA/8	P1	Open	No	240	< 1:30	
May 21	T5A10A2	2-AM10-CL	13	PanA/8	P1	Open	No	60	1:49	
May 21	T6A10A1	2-AM10-CL	13	PanA/8	P2	Open	No	60	2:51	
May 22	T7A10C1	2-AM10-CL	13	1A-Crib	C1	Open	No	120	No	<i>Cycled, also see T6MFC3</i>
May 22	T8A10B*	2-AM10-CL	13	4A-crib	P2	Open	No	120	< 2:00	<i>Large crib = low O2</i>
May 22	T9A10A1	1-A10-DR	13	PanA/8	P1	Open	No	60	< 2:00	<i>Large pan = low O2</i>
May 22	T10A10A1	1-A10-DR	13	PanA/8	P1	Open	No	240	< 2:00	
Appendix 2-B										
Nozzles: Kidde 1214 K ~1:30										
June 8	T11K14A1	2-K14-CL	13	Pan A/8	P1	Open	No	180	< 4:00	
June 8	T12K14A1	2-K14-CL	13	Pan A/8	P1	Open	No	60	4:04	
June 8	T13K14A2	2-K14-CL	13	Pan A/8	P2	Open	No	60	NE	
June 8	T14K0A2	None	None	Pan A/8	P2	Open	No	1000	NE	
June 8	T15K14A2	2-K14-CL	13	Pan A/8	P2	Open	Yes	60	10:50	
June 8	T16K14A2	2-K14-CL	13	Pan A/8	P2	Open	Yes	60	NE	
June 8	T17K14A1	2-K14-CL	13	Pan A/8	P1	Open	Yes	60	3:54	

Table 3. Full-scale Test Index (Continued)

Date 1998	Test #	# Nozzles & Where	System Press. (bar)	Fuel Config.	Position in Room	North Door	South Door	Preburn Time (s)	Exting. Time (min:sec)	Notes
Appendix 2-B (Continued)										
June 9	T18K14C3	2-K14-CL	13	1A Crib	P3	Open	No	180	NE	
June 9	T19K14A1	3K14CL+D	13	Pan A/8	P1	Open (-)	No	60	2:10	
June 9	T20K14A1	3K14CL+D	13	Pan A/8	P2	Open (-)	No	60	2:20	
June 9	T21K14A2	3K14CL+D	13	Pan A/6	P2	Open (-)	Yes	60	NE	<i>Used 6.0 L heptane</i>
June 9	T22K14A2	1K14CL+D	13	Pan A/8	P1	Open (-)	Yes	60	NE	
June 9	T23K14A2	1K14D	13	Pan A/8	P2	Open (-)	No	60	3:00	
June 9	T24K14A2	1K14D	13	Pan A/8	P2	Open (-)	Yes	60	NE	
June 10	T25K14A2	2K14D+V	13	Pan A/8	P2	Open (-)	Yes	60	NE	<i>Pulsed air: exiting 'd'</i>
June 10	T26K14C3	2K14D+V	13	1A Crib	P3	Open (-)	Yes	180	NE	
June 10	T27K14C3	3K14CL+D	13	1A Crib	P3	Open (-)	No	180	NE	
June 10	T28K14C3	2K14CL	13	1A Crib	P3	Open (-)	No	180	NE	
Jul 29	T1 K85 1A	2-K8563-CL	70	Pan A/8	P1	Open	L ½	60	<1:00	<i>Normal pressure 13 bar</i>
Jul 29	T2 K85 2A	2-K8563-CL	70	Pan A/8	P2	Open	L ½	60	<1:00	<i>Normal pressure 13 bar</i>
Jul 28	T3 K85 3C	2-K8563-CL	70	1-A Crib	P3	Open	L ½	180	<1:00	<i>Normal pressure 13 bar</i>
Jul 28	T4 K85 3C	2-K8563-CL	70	1-A Crib	P3	Open	Closed	180	<1:00	<i>Normal pressure 13 bar</i>
Aug 6	T5 K85 3C	2-K8563-CL	12	1-A Crib	P3	Open	L 1/2	180	NE	

Table 3. Full-scale Test Index (Continued)

Date 1998	Test #	# Nozzles & Where	System Press. (bar)	Fuel Config.	Position in Room	North Door	South Door	Preburn Time (s)	Exting. Time (min:sec)	Notes
Appendix 2-C Marioff 4S 1MC 8MB 1100										
Jul 14	T1MFA1	2-M11-CL	70	Pan A/8	P1	Open	Closed	60	<1:00	Fire out rapidly.
Jul 14	T2MFAG1	2-M11-CL	70	Pan A*/8	P1	Open	Closed	60	<1:00	Fire out rapidly
<i>Pan A*/8: A * indicates sheet of gypsum board on top of steel plate, to insulate steel plate from water cooling.</i>										
<i>Conclude that extinguishment at P1 not solely due to cooling of steel plate.</i>										
Jul-14	T3MFA1	2-M11-CL	70	Pan A/8	P1	Open	L 1/3	60	<1:00	Vent'n improved Existing !
Jul-14	T3R-MFA1	2-M11-CL	70	Pan A/8	P1	Open	L 1/3	60	0:19	Confirmed T3MF
Jul-14	T4MFA2	2-M11-CL	70	Pan A/8	P2	Open	L 1/3	60	0:21	
Jul-14	T5MFA2	2-M11-CL	70	Pan A/8	P2	Open	Closed	60	0:14	
Jul-15	T6MFC3	2-M11-CL	70	1A Crib	P3, panel	Open	Closed	180	NE	Long tests, cycled
Jul-15	T7MFC3	2-M11-CL	70	1A Crib	P3, panel	Open	Closed	180	NE	
Jul-15	T8MFC3	2-M11-CL	70	1A Crib	P3, panel	Open	Full Open	180	NE	
Jul-16	T9MF C3	2-M11-D(45)	70	1A Crib	P3, Panel	Open	L 1/2	180	NE	
Jul-30	M1 3S 3C	2 M3S-CL	70	1A Crib	P3	Open	Closed	180	NE	
Jul-30	M2 3S 3C	2 M3S-CL	70	1A Crib	P3	Open	L 1/2	180	NE	
Jul-30	M3 3S 1A	2 M3S-CL	70	Pan A/8	P1	Open	L 1/2	60	0:48	
Jul-30	M4 3S 2A	2 M3S-CL	70	Pan A/8	P2	Open	L 1/2	60	2:50	
Aug 11	T10 MF 3CC	2-M4S 1MC 8MB 1100-CL	70	1-A Crib + ceiling	P3	Open	L1/2	180	NE	Fire began very slowly; different than other tests.
Aug 11	T11 MF 3CC Repeats T10...	2-M4S 1MC 8MB 1100-CL	70	1-A Crib + ceiling	P3	Open	L1/2	180	NE	Redo T10: fire growth more typical. Better test.
Aug 12	T12 MF1 3C	1 MF11 MCL	70	1-A crib	P3	Open	L1/2	180	NE	Fire ventilation-limited.

Table 3. Full-scale Test Index (Continued)

Date 1998	Test #	# Nozzles & Where	System Press. (bar)	Fuel Config.	Position in Room	North Door	South Door	Preburn Time (s)	Exting. Time (min:sec)	Notes
Appendix 2-D: Navy Nozzles at 70 and 12 bar										
Jul-28	T1Na1A	2-Na-CL	70	Pan A/8	P1	Open		60	<0:30	
Jul-28	T2Na2A	2-Na-CL	70	Pan A/8	P2	Open		60	<0:30	
Jul-28	T3Na3C	2-Na-CL	70	1-A Crib	P3	Open		180	NE	
Jul-28	T4Na3C	2-Na-CL	70	1-A Crib	P3	Open		180	NE	
Aug 6	T5 Na 3C	2-Na-CL	12	1-A Crib	P3	Open	L1/2	180	NE	<i>Poor performance due to low water pressure</i>
Aug 11	T6 NA 3CC	2-NA - CL	70	1-A Crib + ceiling	P3	Open	L1/2	180	NE	<i>Fire growth typical. Fire damage very limited.</i>
Aug 12	T7 NA1 3C	1 NA MCL	70	1-A Crib	P3	Open	L1/2	180	NE	<i>Damage exceeds T12 MF1</i>
Appendix 2-E: Unsuppressed Fires										
June 8	T14K0A2	None	None	Pan A/8	P2	Open	No	1000		<i>Unsuppressed pan fire</i>
Aug 12	T8 N0 3C	None	0	1-A Crib	P3	Open	L1/2	---		<i>Unsuppressed crib fire</i>
Aug 13	T9 N0 3C	None	0	1-A Crib	P3	Open	L1/2	---		<i>Redo unsuppressed fire</i>
				Total = 59						

3.6 Analysis and Key Findings

The objective of the Task 2 experimentation was to obtain information to guide the design of an optimized water mist system that will provide flashover suppression as a minimum. Other benefits, such as smoke-hazard mitigation, extinguishment, would be gratuitous. The analysis of the data is presented through a series of questions relating to possible design criteria. Plots and comparisons are provided to support or disprove particular hypotheses.

With reference to the ‘questions’ A and B in Table 2, a number of observations can be made.

- A. (Type of fuel package). Although the heptane pan fires allowed investigation of the cooling effectiveness of water mist, they were too easily extinguished in the ventilation limited compartment. The 4-A wood crib created a fire that was larger than was desired for investigating the lower limit of performance. The 1-A crib plus combustible wall panel fuel package created a fire that was slow in developing, but capable of bringing the room to flashover. The early stages of the crib fire were similar to a waste basket fire, followed by involvement of wall surfaces. Because of the charred embers, the crib could burn at variable rates of combustion, governed by the amount of water vapor, oxygen and cooling. If nozzles had been closely spaced, or arranged to discharge directly onto the crib, the crib and the wall panels would likely have been extinguished. For this system, intended to provide only flashover suppression, the nozzles were not located so as to extinguish. This means then, even if the ‘waste-basket fire’ had been detected early by a sensitive smoke detection device, and then if the mist had been activated early, the fire would still have grown as it did in this test series. The function of the mist system was to prevent the small fire from growing large enough to flashover the compartment.
- B. For pan fires in the middle areas of the compartment, the pan “under one” nozzle was more easily extinguished than the pan “between two” nozzles. With the low pressure (AM10 and K14) nozzles it was possible to sustain an unextinguished pan fire in either location for 2 or 3 minutes. With the high pressure Marioff nozzle, the pan fires in either location were extinguished almost instantaneously (< 2 s). Increasing the ventilation to the compartment increased the extinguishment time to about 20 seconds. This was further reason for concentrating on the corner crib fire scenario to investigate flashover suppression independently of extinguishing effectiveness.

Questions’ C through G in Table 2 are discussed in the following sections.

3.6.1 Flashover Suppression

In all of the tests in which water mist was activated, temperatures in the compartment were controlled to the extent that the potential for flashover was eliminated.

The effects of water mist on compartment temperatures are illustrated in Figures 13 to 17. Figure 14 shows the thermocouple readings versus time for the TC trees inside the fire test room, for an unsuppressed wood crib fire. Figures 15 and 16 show the same TC trees during suppressed fires. Individual TC trees record different temperatures because they are at different distances from the fire. The invariable pattern for suppressed fires is that the temperatures peak just before activation of the mist; temperatures drop after the mist is turned on. As has been explained, the water mist does not extinguish the crib fire. The fire burns at a reduced rate, gases are mixed and cooled in the compartment, and the compartment comes to a steady-state temperature condition. That steady state temperature condition may be higher, or lower, depending on the efficiency of the mist being applied.

It is also evident from comparing Figures 15 and 16 that the type of nozzles and/or their location affect 'how soon' the temperatures change from increasing to decreasing. In Figure 15, Test 18 (nozzles in the center of the room), the fire responded almost immediately after the mist was turned on. In Figure 16 for Test 26, the fire was much smaller at the time of activation and the nozzles were located at the door, much farther from the fire. When the mist was activated, the temperature rise slowed for several minutes, probably due to reduced air entering the room. After a few more minutes, the fire became established and grew. Eventually the compartment was warm enough to create a buoyancy-driven pressure difference strong enough to overcome the mist-obstacle at the door, and draw in the air it needed to burn. After a period of time, conditions in the compartment settled to a steady-state condition similar to other fires, and other nozzle locations.

The magnitude of the cooling of compartment temperatures by water mist is illustrated by the temperature profiles in Figures 13 and 17. These plots compare vertical temperature profiles at specific times in the compartment (TR2), and in the corridor (TR5). The vertical profile shows the temperature at each thermocouple (abscissa) versus the elevation above the floor (ordinate). Figure 13 shows the temperature profile for an unsuppressed crib fire: ceiling temperatures at TR2 attain 400°C at the time of peak burning (360 s after ignition in Figure 14). Between the ceiling and the floor, the temperature drops from 400°C to 130°C. In this test, the tops of target cardboard boxes ignited at mid-height, indicating that the room was approaching flashover. Even the conditions in the corridor (TR5) were very hot above 1.0 m, rising to 260°C.

The same figure shows temperature profiles at times of stable conditions for Tests 18 and 26. In Test 18, two nozzles were located on the centerline of the room, 3.35 m apart. The nozzles were 'distributed' within the area of the compartment. Temperatures at the ceiling did not exceed 130°C. In Test 26, two nozzles were located in front of the two ventilation openings, the main door and the south vent. Thus there was no distribution of spray in the interior of the room. One would expect there to be less cooling/mixing than Test 18. In fact the temperature at the ceiling is only slightly higher (150°C) than Test 18. The significant point in this comparison is that in both tests, temperatures inside the compartment were well below any point of concern about flashover.

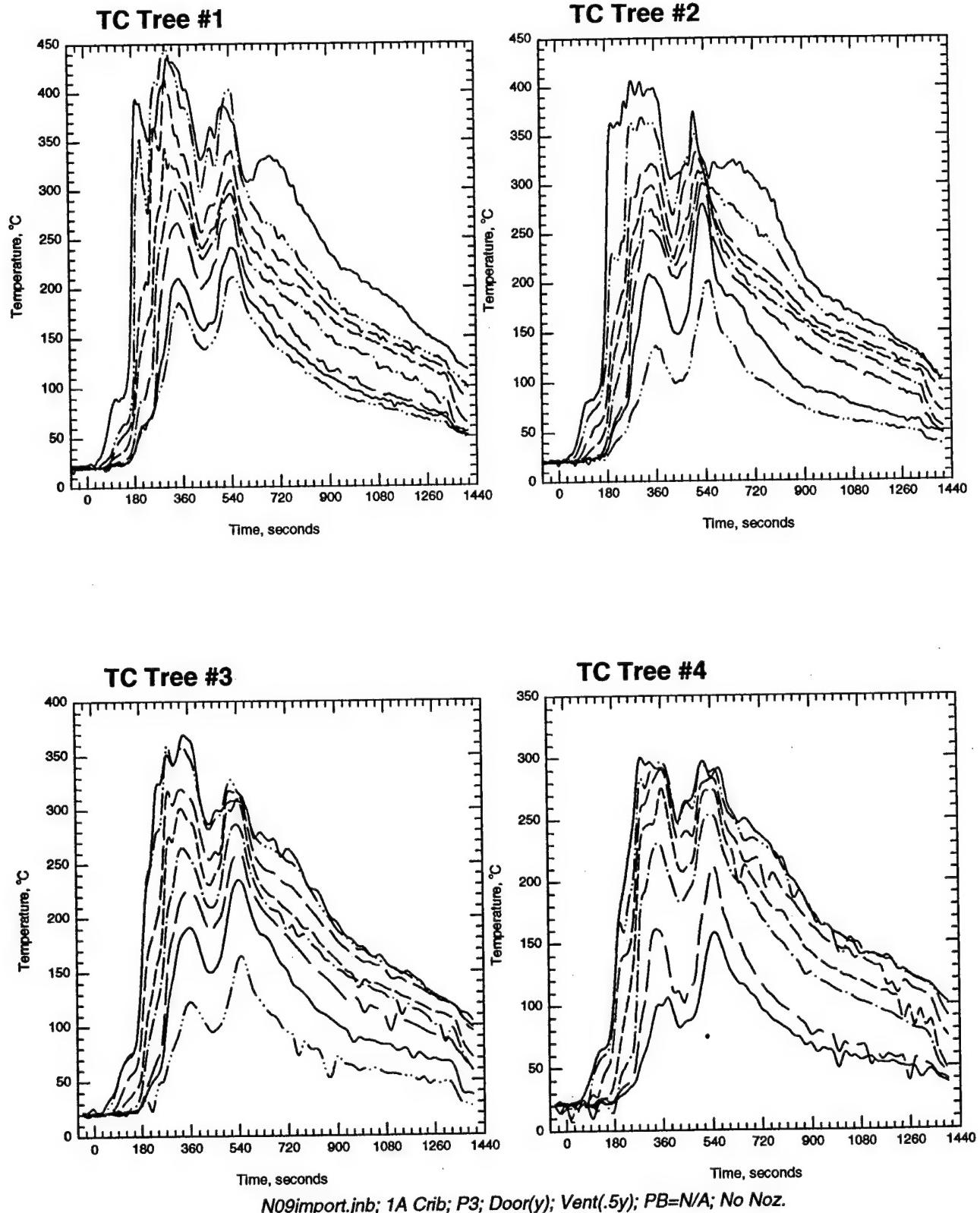
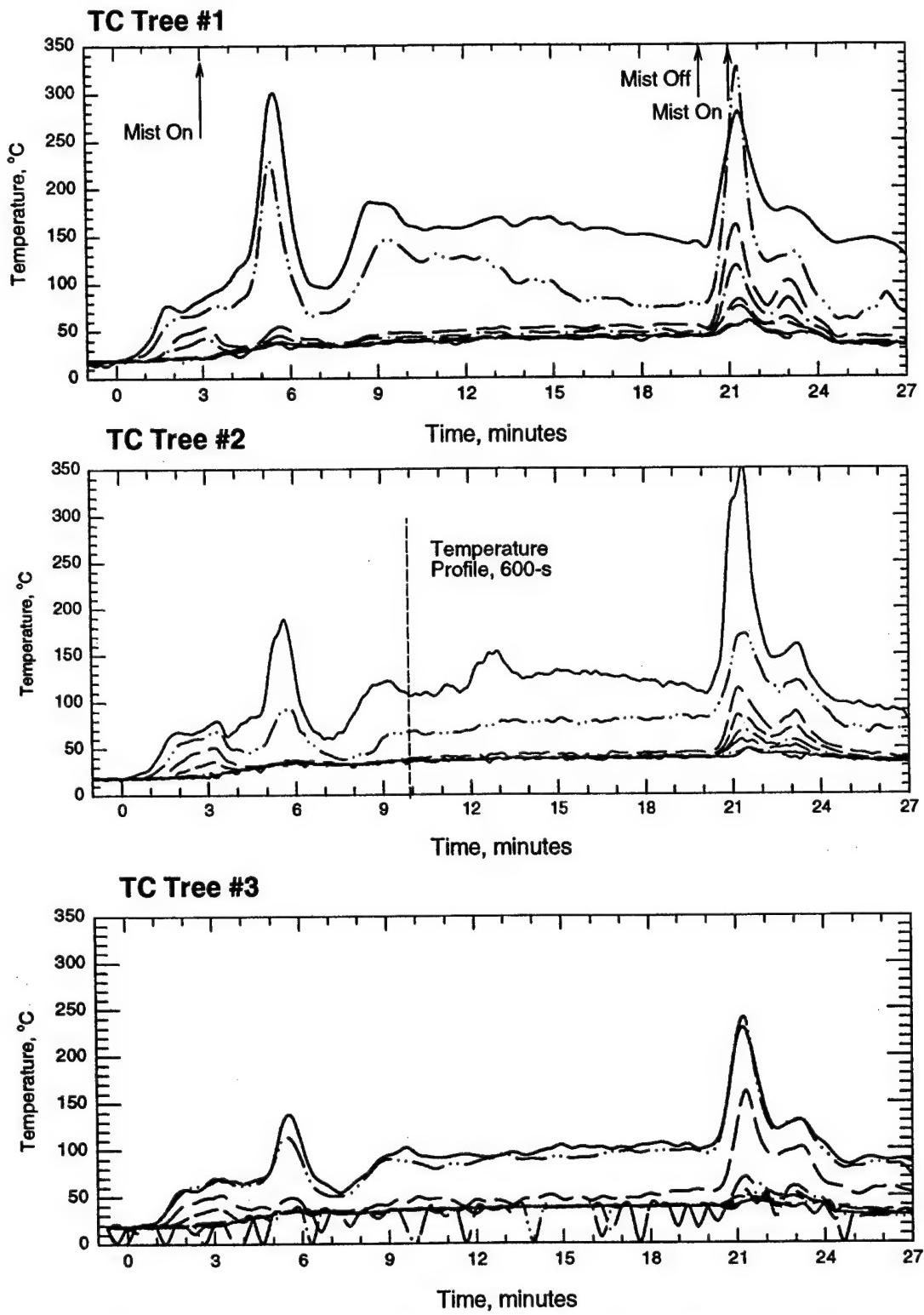


Fig. 14 – Thermocouple trees #1 to #4 in fire test room for Test T9N03C

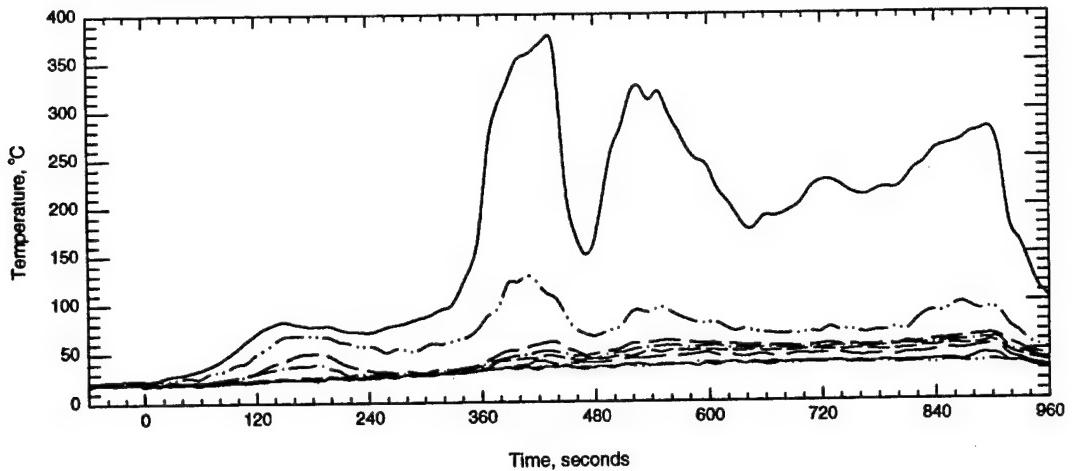
T18 K14 C3: Wood crib + wall panels, 2 - K14-CL



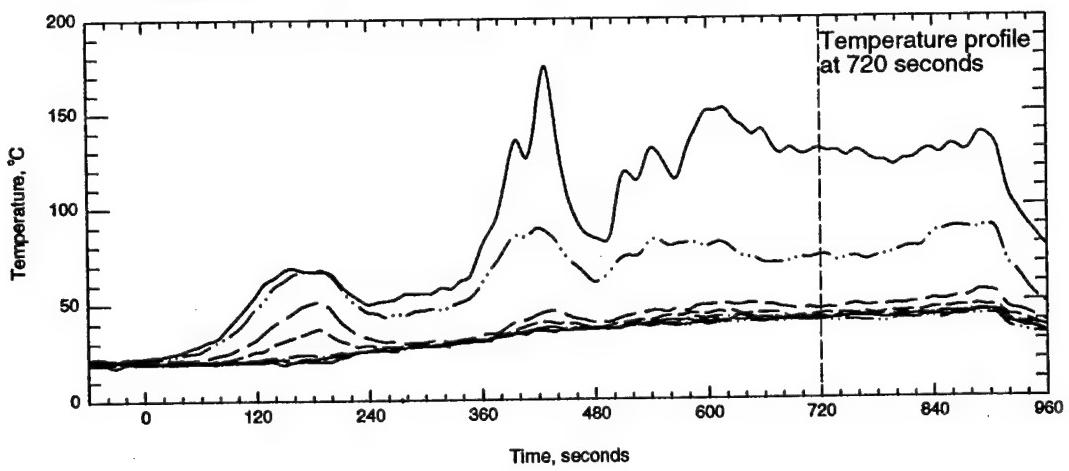
TestnT18K14C3: 1A Crib; P3; Door (y); Vent (n); PB=180s; 2-K14's on CL; 190 psi.

Fig. 15 – Temperature versus time at thermocouple trees #1 and #3

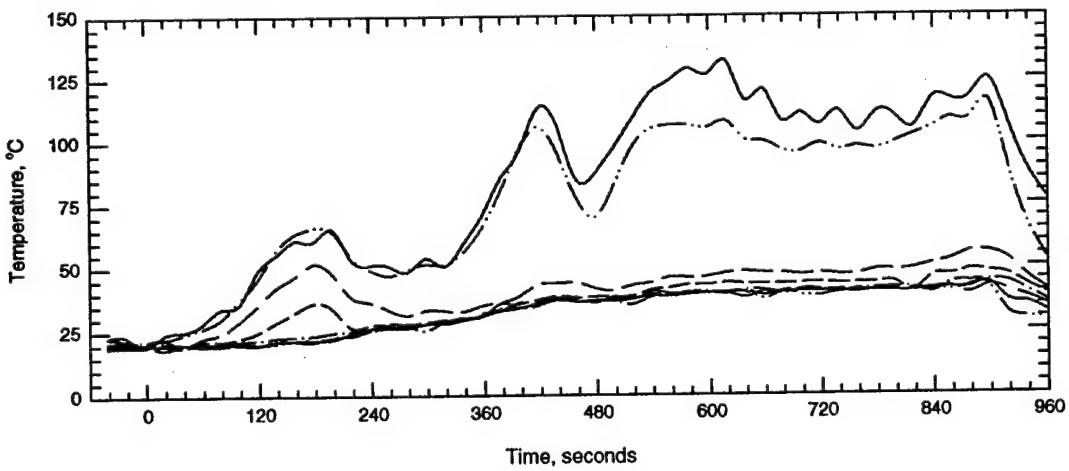
TC Tree #1



TC Tree #2



TC Tree #3



T26K14: 1A Crib; P3; Door(-y); Vent(y); PB=180s; 1-K14-D+V; 190 psi.

Fig. 16 – Thermocouple trees in fire test room for Test T26K14C3

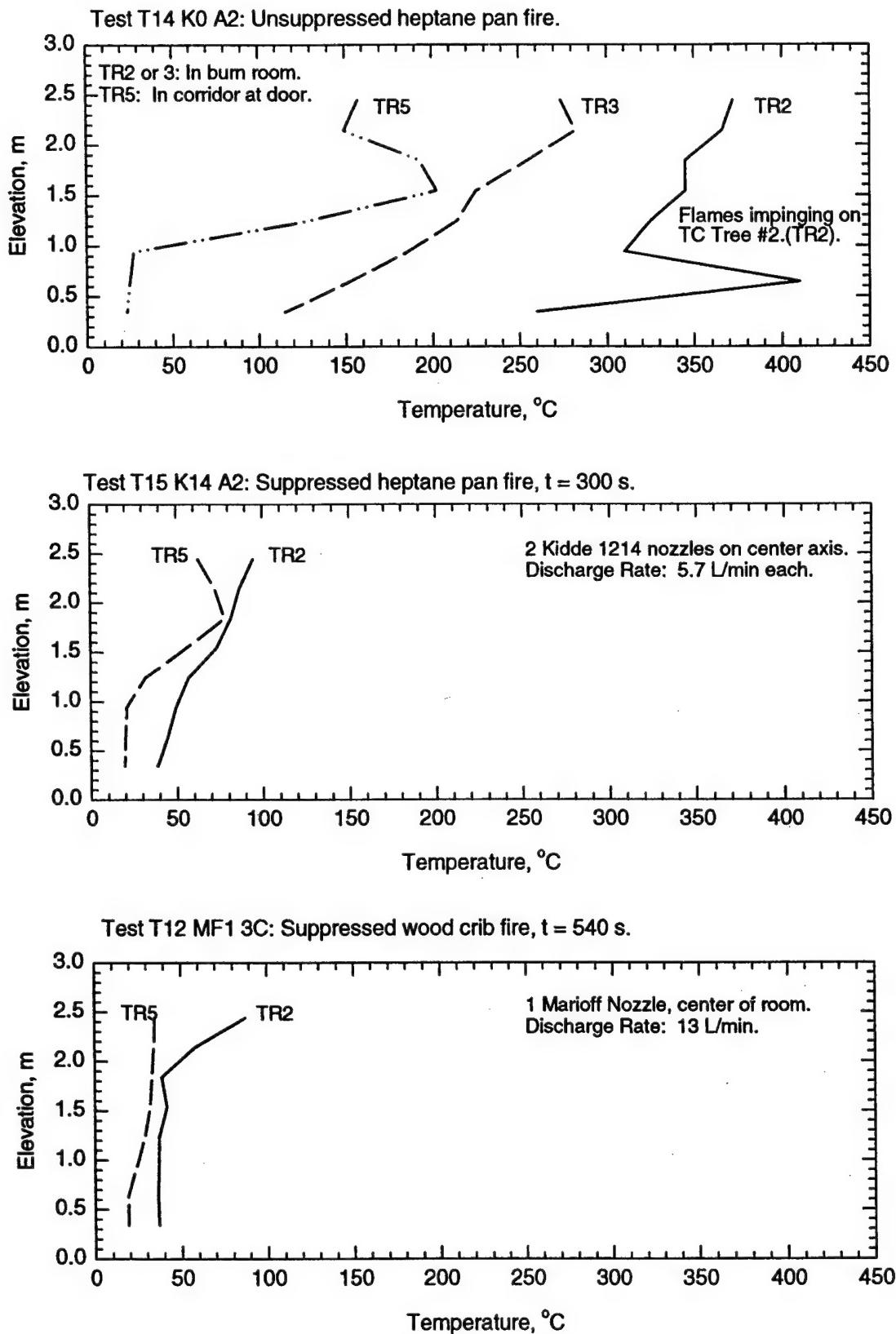


Fig. 17 – Temperature profiles in room and in corridor, > 1 minute duration

Temperatures outside the compartment at TR5 were cooler in Test 26 than in Test 18. In Test 26, nozzles were positioned over the door rather than distributed in the room. Even though the interior of the compartment was warmer than with distributed nozzles in Test 18, the door nozzle was more effective than the interior nozzles at cooling the gases leaving the compartment.

Figure 17 shows vertical temperature profiles in the compartment for an unsuppressed heptane pan fire (Test T14A10), and a suppressed pan fire (Test T15-K14). Again, the presence of water spray achieved temperature control regardless of the efficiency of the nozzle, whether two nozzles or one nozzle was used; whether nozzles were distributed in the compartment or placed only over the door. Individual differences in spacing or spray characteristics resulted in differences in ceiling temperatures and vertical profiles, but those differences were refinements in an already-adequate level of control.

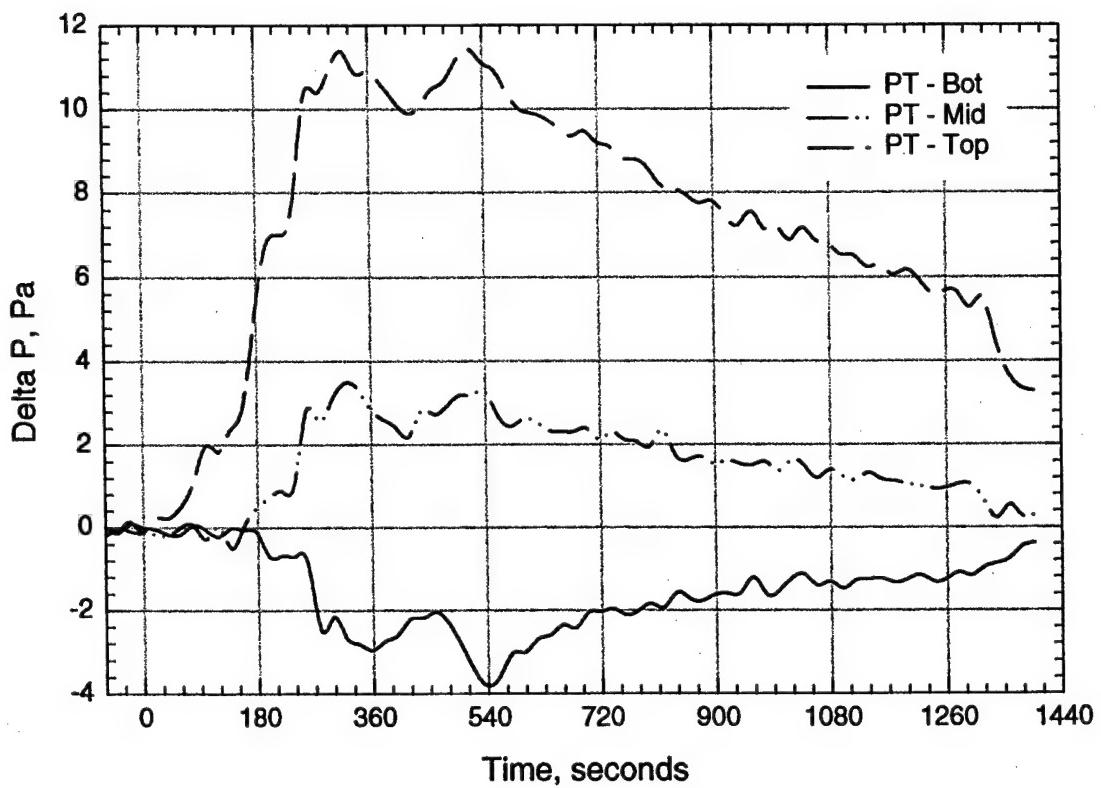
Achieving flashover suppression has a direct benefit for boundary cooling objectives. If a compartment is prevented from becoming hot, there will be no heat transfer to adjacent compartments, and ignition of Class A combustibles will not occur. The only exception to this is where a deep-seated fire is directly against a bulkhead. A local hot spot may eventually cause ignition on the other side of the bulkhead.

Figures 18 and 19 support the point made earlier that there are other indicators of uncontrolled fire than thermocouple readings. Individual thermocouple readings in a compartment will vary greatly depending on elevation, and their proximity to the fire or to the sources of ventilation air. However, the overall compartment pressure, relative to adjacent spaces, is an indicator of how much of the volume of the air in the compartment has been heated. The temperature-driven buoyancy forces generate a pressure difference across enclosure walls. Figure 18 shows that without suppression, the 'delta P' near ceiling level was close to +10 Pa, relative to the non-fire side of the wall. Near the floor, the Delta P was close to -3 Pa, a measure of the strength of the 'suction' pressure exerted by the fire to draw air to itself. Figure 19 shows that, with the application of mist in Test 18, even though the fire is not extinguished, the positive delta P is reduced to +3 Pa, and the negative pressure to -1 Pa.

The plots of compartment pressure reveal two significant benefits of using the water mist to cool the fire gases, i.e., for flashover suppression. Reduced temperatures mean reduced buoyancy forces, which in turn means there is less energy to cause smoke to spread through the corridors of the ship. And, there is less energy available to draw air in to feed the fire. Given the natural restriction to air flow due to narrow corridors and closed doors already present on a ship, the cooling affected by the water mist makes it even more difficult for the fire to find the air it needs to burn vigorously.

Sensing pressure differences across compartment boundaries could be used as an indicator of the state of conditions in a compartment, with a narrower range or variability than individual temperature sensors.

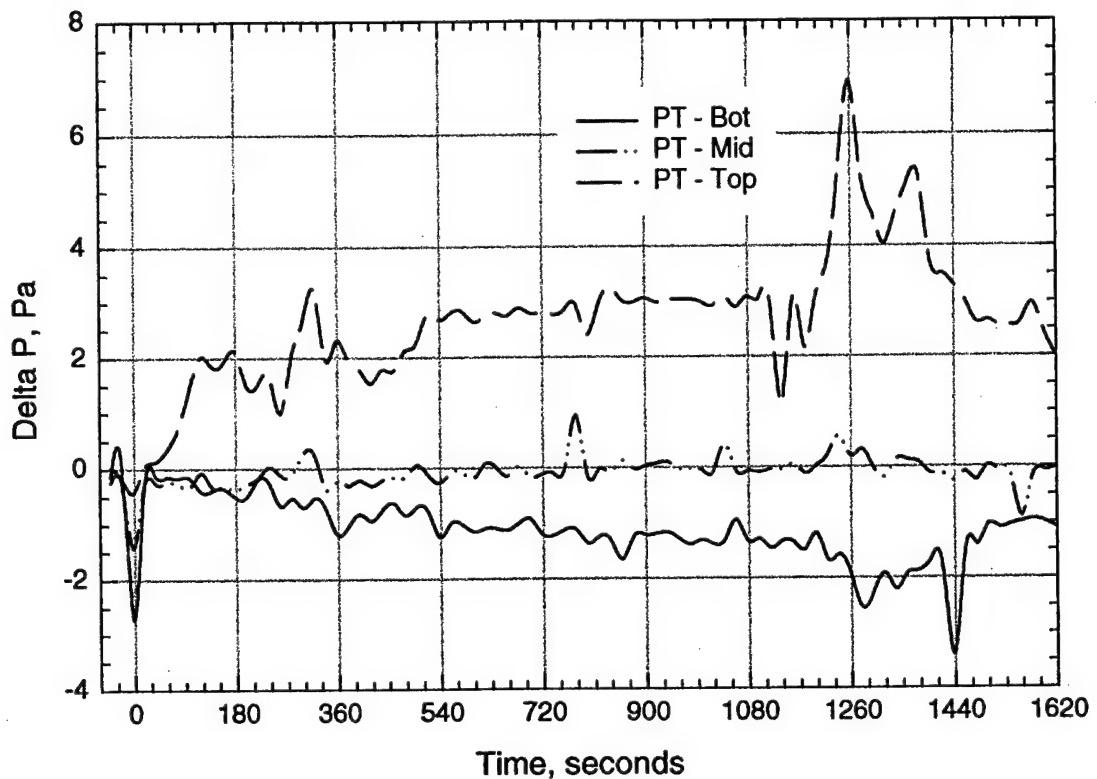
Room Pressure



N09import.jnb; 1A Crib; P3; Door(y); Vent(.5y); PB=N/A; No Noz.

Fig. 18 – Pressure difference between fire test room and adjacent space for Test T9N03C

Room Pressure - Test T18K14C3



test18import.jnb; 1A Crib; P3; Door(y); Vent(n); PB=180s; 2-K14-CL; 190 psi.

Fig. 19 – Pressure difference between fire test room and adjacent space for Test T18K14C3

3.6.2 Effect of Nozzle Location and Spacing

Fire tests were conducted with up to five nozzles in the compartment (T1-A10), with only two nozzles on the centerline, one nozzle on the centerline, and with various combinations of centerline nozzles plus door nozzles. The following statements can be made.

1. In the small, ventilation limited compartment, close spacing of nozzles resulted in rapid extinguishment of both heptane pan fires and wood crib fires. Flashover suppression was achieved without resorting to close nozzle spacing. Close nozzle spacing could be quantified, in the limit, as having 'overlapping or tangent spray cones.'
2. With two nozzles on the center line of the room (a nominal 3.35 m x 3.66 m spacing), the objective of flashover suppression was easily achieved with all nozzles. The distance between nozzles was larger than the diameter of the spray cones;
3. With nozzles placed over the door way to cut-off air flow into the compartment, and to cool gases before they leave the compartment, the flashover suppression objective was also met. In this case, the "nozzle spacing" is approximately the dimensions of the compartment. However, temperatures inside the compartment were higher than when nozzles were distributed in the room area. As mentioned above, higher compartment temperatures are a disadvantage with respect to the flow of smoke out, and the flow of fresh air into, the compartment. Thus, although in these tests the flashover suppression objective was met with door nozzles only, nozzles distributed so as to achieve better cooling inside the compartment are a more robust choice. If the temperatures are reduced in the compartment over a large area, the buoyancy pressure will be much less than if the gases are cooled locally at a point of passage out of the compartment. Therefore, distributed spacing is better than trying to mitigate fire severity by installing nozzles at a few strategic points;
4. Compartment cooling was achieved with two nozzles spaced 3.35 m apart with spray cone diameters as low as 1.2 m. The flux density measurements revealed that in spite of the 'fineness' of the water mist, it is not distributed uniformly throughout the compartment. Most of the mass of water is deposited within the spray cone area of each nozzle. Thus, the concept of averaging the total nozzle flow rate over the floor area of the compartment (a nominal flux density) for use as a design parameter, does not accurately relate to how the mist benefit is achieved. In the test room, two Kidde 1214 nozzles with 1.2 m diameter spray cones (combined area = 2.26 m²) "covered" approximately 9 percent of the total floor area. Nozzles with spray cone diameters closer to 1.7 m (the Marioff nozzles),

- 'covered' approximately 19 percent of the total floor area, with no change in nozzle spacing, and similar flow rates;
5. The Marioff nozzles did perform "better" than the other nozzles, including the Navy nozzle. This was clearly evident in the rapid extinguishment of pan fires in Tests T1MF- to T4MF- compared to Kidde nozzles. Figure 20 compares the average oxygen concentrations in gases measured 410 mm below the ceiling above the door, for tests using two Kidde nozzles and a single Marioff nozzle. With the Kidde nozzles, the oxygen concentration dropped to about 15 percent in both fire scenarios. That condition was stable for many minutes. In Test T12MF11, a single Marioff nozzle in the center of the room almost extinguished the wood crib fire, so that oxygen concentrations stabilized in the vicinity of 18 percent. The higher level of oxygen concentration during the steady state, indicates that the Marioff nozzle was doing a 'better job' of suppressing the wood crib fire than the other nozzles; and
 6. The measurably better performance of the Marioff nozzle cannot be associated simply with either spacing, or flux density factors. Two characteristics which are distinct to that nozzle are the very fine drop size distribution ($D_{v0.9}$ of 190 microns), and the high energy available for mixing, as can be expressed in terms of the 'power coefficient.' Also, the distinct regions of high and low flux density within the cone, and high and low velocity, described in Section 2, may contribute to improved mixing, hence better cooling and suppression.

3.6.3 Impact of Ventilation on Mist System Performance

A number of measures were taken to evaluate how closely the performance was determined by the limited ventilation in the test room. It was found necessary to add a second navy door ventilation opening early in the test program, to be able to bring the room to near flashover conditions, and also to be able to apply any amount of water mist without extinguishing the fire. The fire scenarios in the room were clearly sensitive to the limited ventilation. The scenario of the unextinguished wood crib fire, with burning wall panels, and mist applied for cooling only, resulted in a more or less stable temperature regime in the compartment. The fire in the wood crib was suppressed to a state of glowing embers. An unextinguished heptane pan fire was 'struggling' erratically above the pan. Any change in either the water mist application rate, or in the ventilation to the compartment, during this stable period resulted in a rapid re-growth of the fire and a corresponding rise in temperature in thermocouples closest to the fire.

Figure 20, from Test T25K14A2, illustrates the sensitivity of the tests to a change in ventilation during the 'control' period. The side door to the room was opened at 320 seconds. This could be equated to opening a second doorway into a compartment for entry for damage control action. No change was made to the water flow rate. The thermocouples in TC Tree #2

Room Gas Concentrations (%), 0.46 m below ceiling.

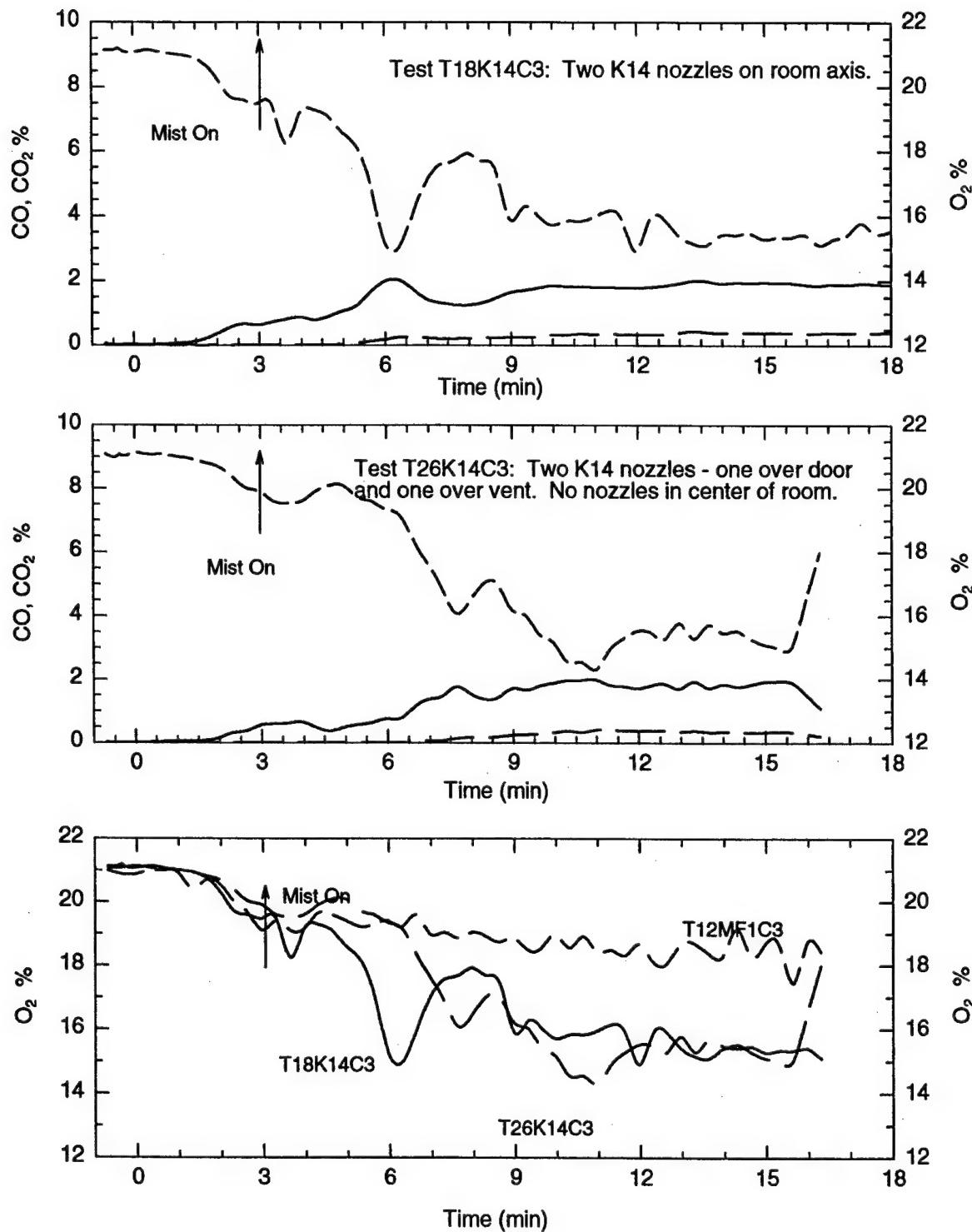


Fig. 20 – Comparisons of the effect of different nozzle types on rate of O₂ consumption for the 1A crib + corner panel fires

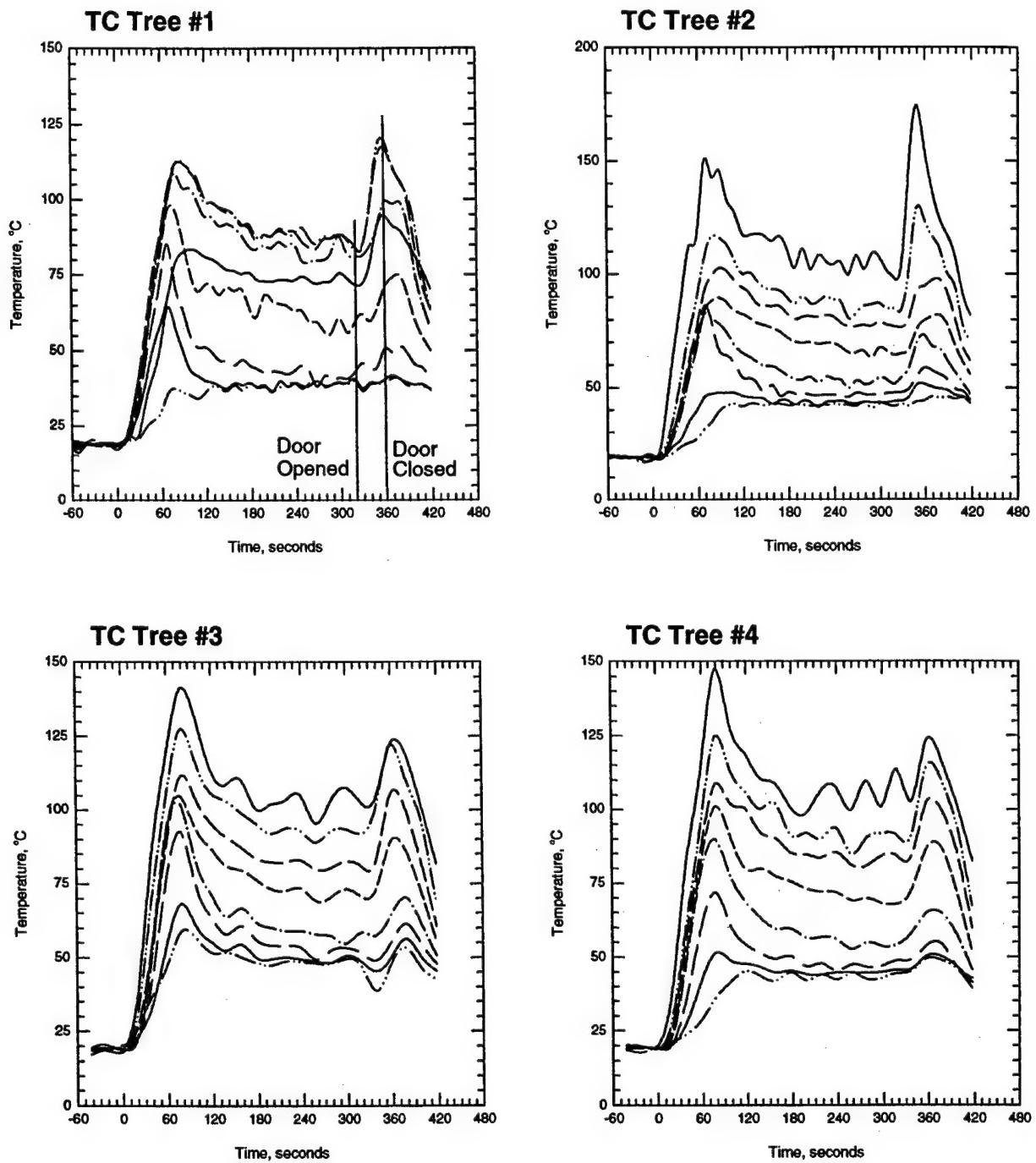
responded immediately to the re-growth of flame initiated by entry of air through the new opening. In this fire, the door was held open for 22 seconds, then closed. Immediately after closing the door, the fire extinguished. There are a number of factors that explain this phenomenon – relating to extinguishment by oxygen depletion, fuel vapor dilution by water vapor, etc. Test T28-K14 showed a similar rapid response of a crib fire to opening the side door to the compartment. Unlike the heptane fire, however, it did not extinguish when the door was re-closed. The glowing embers of the wood crib are much harder to extinguish than heptane. The test data illustrates that the level of temperature control that was achieved was very sensitive to the ventilation conditions. Noting this, the following statement can be made:

1. The temperature reduction that can be achieved by water mist in a compartment is affected by not only the rate of application of mist, but also by the ventilation available to support combustion. To set design parameters for a water mist system will require that the ventilation condition be defined;
2. A breach in a compartment designed for minimal flow rates for flashover suppression could lead to quick re-growth in fire intensity. This breach could be due to battle damage or to entry of a damage control crew through a previously closed opening; and
3. The primary implication of the evident sensitivity to ventilation conditions is that although flashover suppression can be achieved with very low application rates, and very few nozzles per compartment, control over ventilation can be lost in a variety of ways. In order to also have ‘robustness’ in a system, the design objective should be raised toward achieving extinguishment.

3.6.4 Spray Cycling

Figures 21 and 22 are from Test T7A10C1. A 1-A wood crib in the corner was suppressed by two AM10 nozzles on the centerline of the room. The room had been in a stable temperature regime for a number of minutes, when the water was shut off at about 1020 s. The glowing embers in the wood crib immediately responded by growing back into a flaming fire. Figure 22 shows that the oxygen concentration at mid-height in the room also dropped rapidly at that time. It is evident, then, that the rapid temperature increase in the thermocouple plots was due to increase in heat release rate of the fire, i.e., re-growth of fire in the embers of the crib. If temperatures had responded, but not the oxygen sensor, the temperature change might be attributed to loss of radiation attenuation when the mist was shut off. However, because temperature and oxygen concentration responded strongly to the on-off action of the water mist system, the control exercised by the water mist is due primarily to suppressing the burning rate of the fuel.

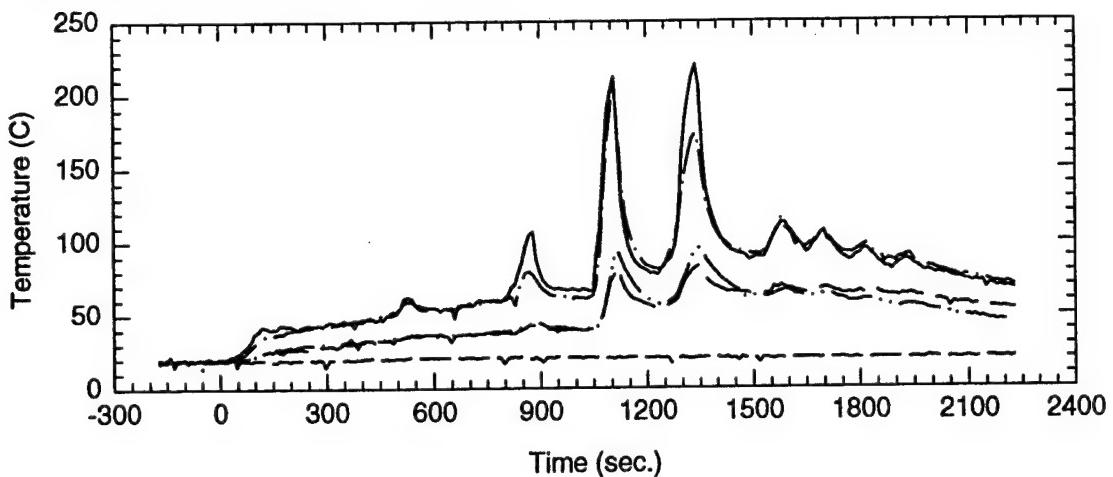
In Test T6-MF-C3 with a Marioff nozzle, it appeared that the first application of water mist had completely extinguished the wood crib fire. After a two minutes with no apparent fire,



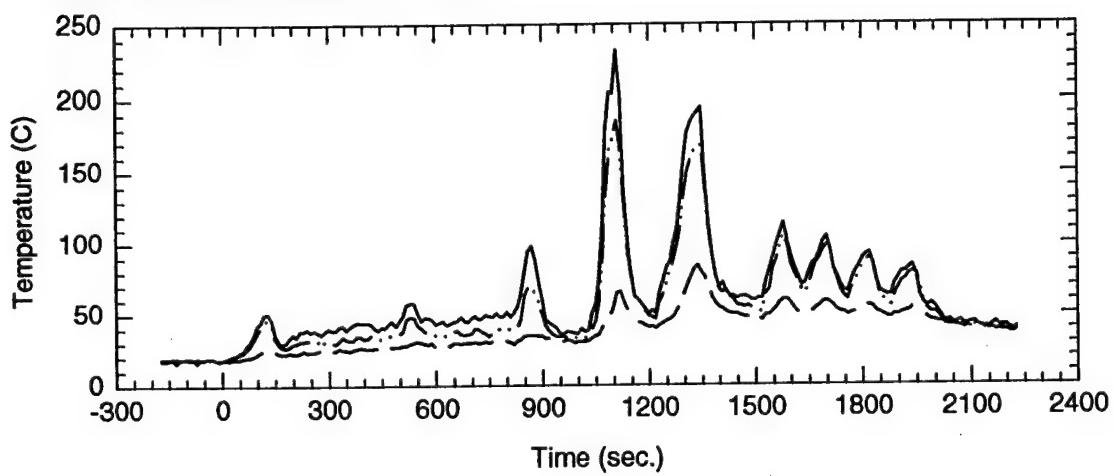
test25import.jnb; Pan A/8; P2; Door(-y); Vent(y); PB=60s; 1-K14-D+V; 190 psi.

Fig. 21 – Thermocouple trees in fire test room for Test T25K14A2

Ceiling TCs directly over fire - TC 64-68



Ceiling TCs toward the door - TC 69-71



Ceiling TCs throughout the corridor - TC 72-77

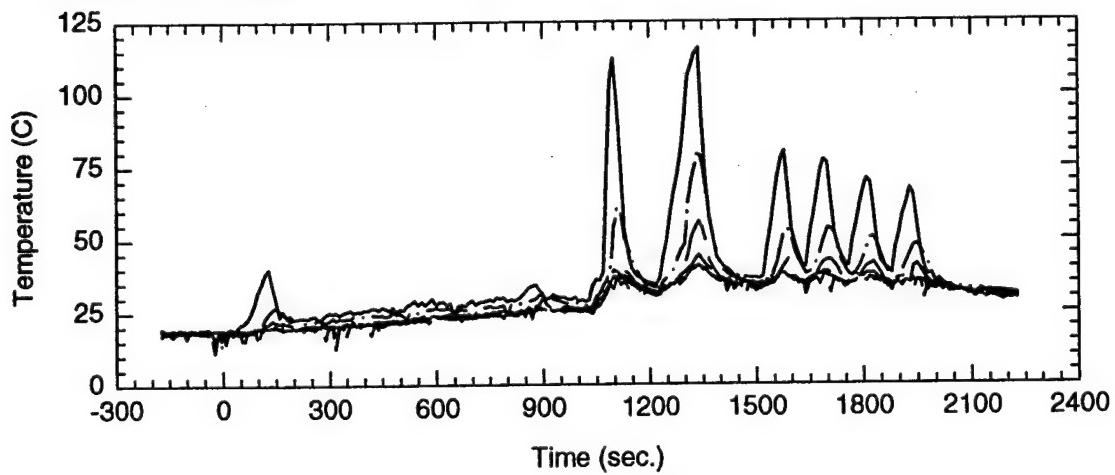


Fig. 22 – Ceiling temperatures in burn room and corridor for Test T7A10C1

the water mist was shut off. At that point, it became evident that the fire had not been extinguished: compartment temperatures shot up rapidly.

From the above evidence, the following statement can be made.

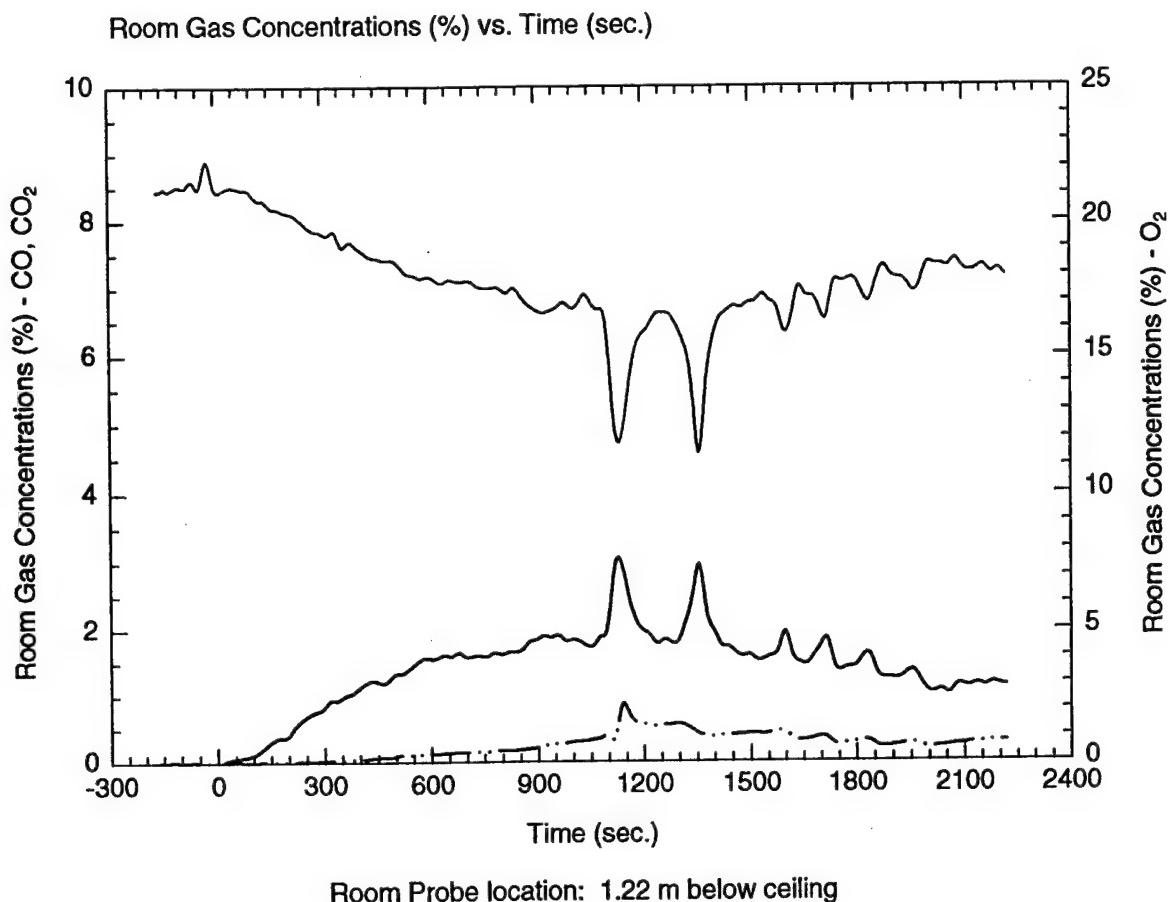
Cycling, i.e., repeated on-off-on action of the water mist as a means to reduce the quantity of water needed, does not appear to be a good idea for fire scenarios involving Class A fuels. Each time the system is shut off, the fire becomes better established in the fuel. When the mist is turned on again, the fire reduces, but to a higher level of burning than before it was shut off. This may be less true for systems designed with the intent to fully extinguish a fire than for a system designed for flashover suppression.

3.6.5 Effect of Water Mist on Smoke Conditions

Optical density meters were mounted on "smoke wells" installed in the ceiling of the test room and the adjacent corridor. It was hypothesized that if the water mist had any effect on the quality of the smoke, it should be evident by a reduced optical density. The optical density meters installed at eye-level in the room and the corridor provide some indication of changes in optical density (Figure 23). The readings are sometimes ambiguous, however, because the smoke conditions at eye-level may be altered by a change in the height of the neutral plane, by dynamic mixing as mist pushes smoke to the floor, and other non-reproducible factors. The smoke moving across the ceiling, on the other hand, and entering the smoke wells, ought to be free of the dynamic changes which affect readings at the other locations. By comparing optical density measurements between smoke from the ceiling of the test room, and from the ceiling of the corridor, any benefits of scrubbing by water mist could be observed.

Figure 24 shows the ODM readings for an unsuppressed wood crib fire – at between 3.0 and 4.0 in both smoke-wells. Figure 25 compares smoke well ODM readings over three test conditions – Tests 17, 18 and 26. In Test 17, (pan fire) smoke from the room is slightly more optically dense than smoke from the corridor ceiling (1.5 and 1.0 respectively), which is less than one half of that seen in the unsuppressed crib fire. For the suppressed wood crib fire, the readings are approximately twice as high as the heptane pan fire condition – 3.0 in the room and 2.5 m^{-1} in the corridor. In Test 26, in which the nozzle is installed over the door only, the optical density of the smoke in the corridor ceiling appears to be higher than in the fire room. This could be due to the fact that there is very little steam generated in the room, and the fire gases are much hotter than in the corridor. The fire gases that have passed through the water mist into the corridor have increased load of water vapor and condensed steam.

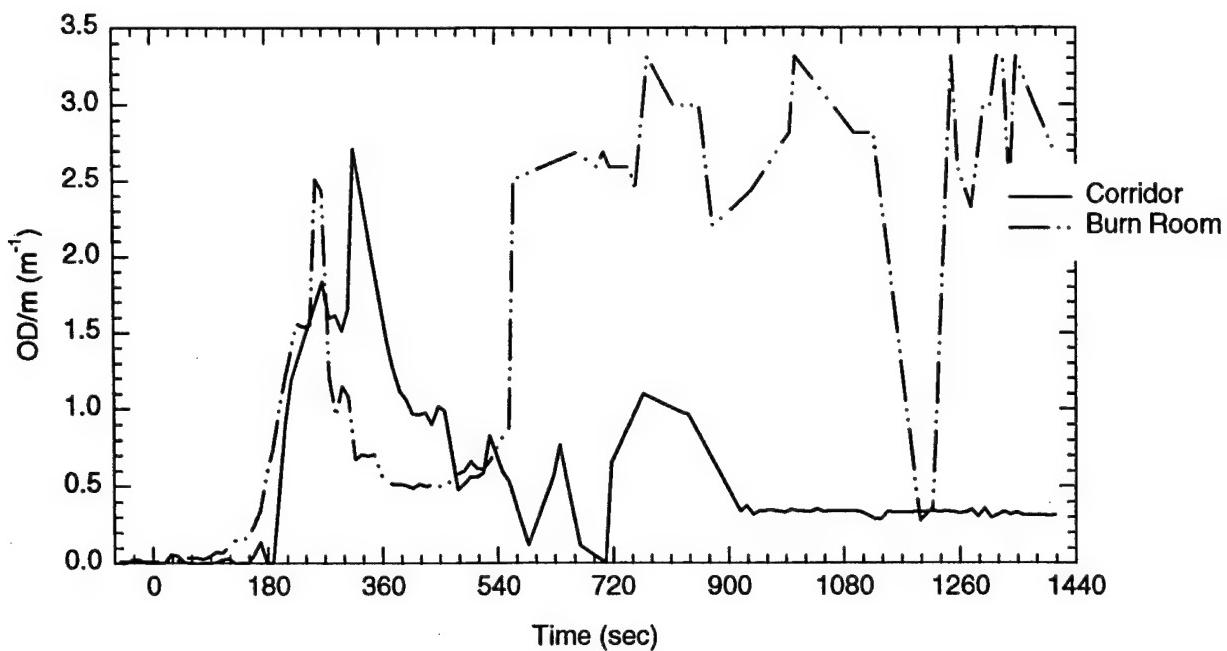
The optical density of the smoke appears to be affected by factors such as the temperature of the smoke, the type of fuel it is generated from, and the presence of steam. As stated above, the eye-level visibility in a smoke-filled corridor may be affected by many factors in addition to the presence of water mist nozzles. The optical density data in these experiments does not



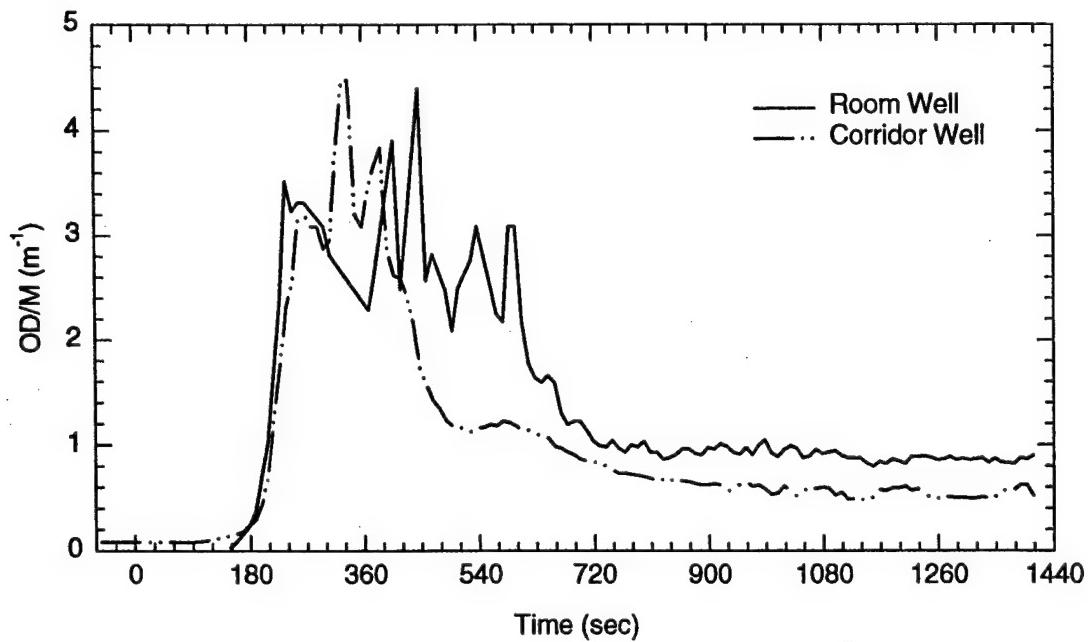
test7import.jnb; 1A Crib; C1; Door(y); Vent(n); PB=120s; 2-AM10-CL; 13.1 bar

Fig. 23 – Room gas concentrations for Test T7A10C1

Room ODM's



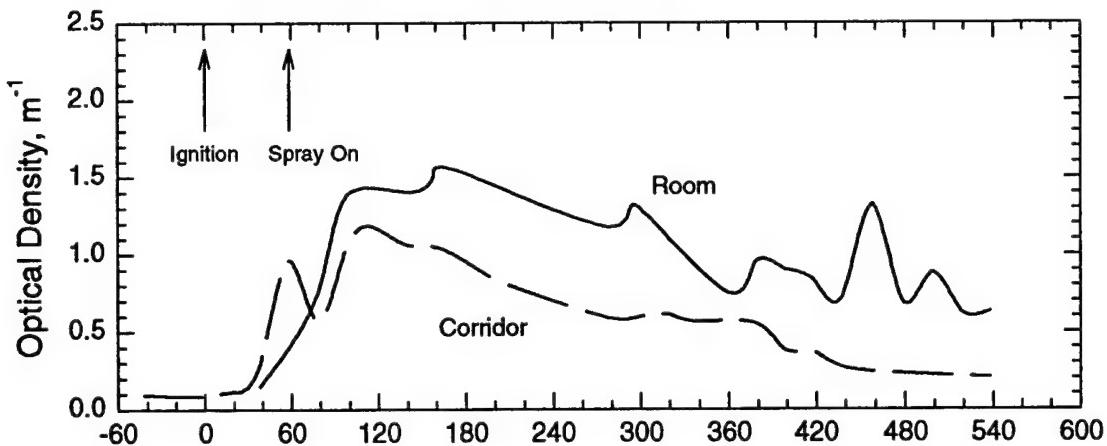
ODM - Smoke Wells



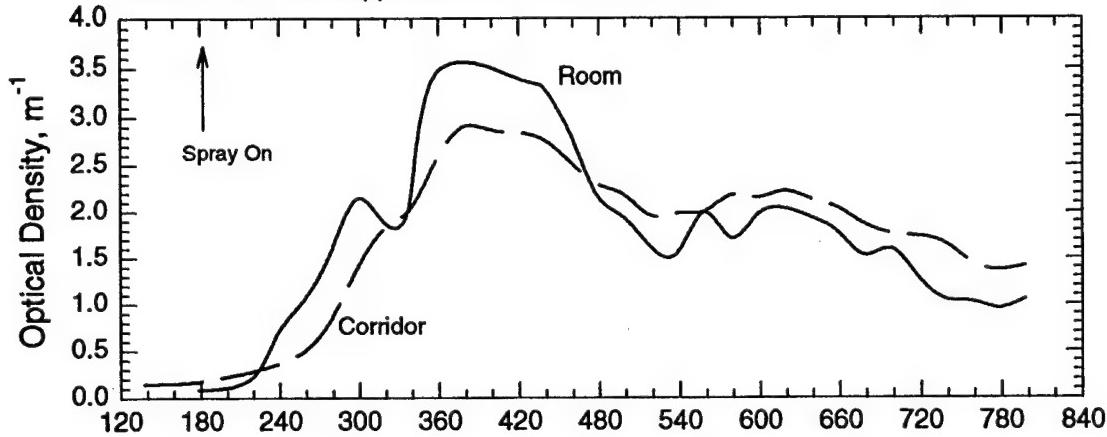
N09import2.jnb; 1A Crib; P3; Door(y); Vent(.5y); PB=N/A; No Noz.

Fig. 24 – Smoke optical density readings for Test T9N03C

Test T17 K14 A1: Suppressed Pan Fire, 2-K14-CL.



Test T18 K14 C3: Suppressed crib fire, 2-K14-CL



Test T26 K14 C3: Partially suppressed crib fire, door nozzles only.

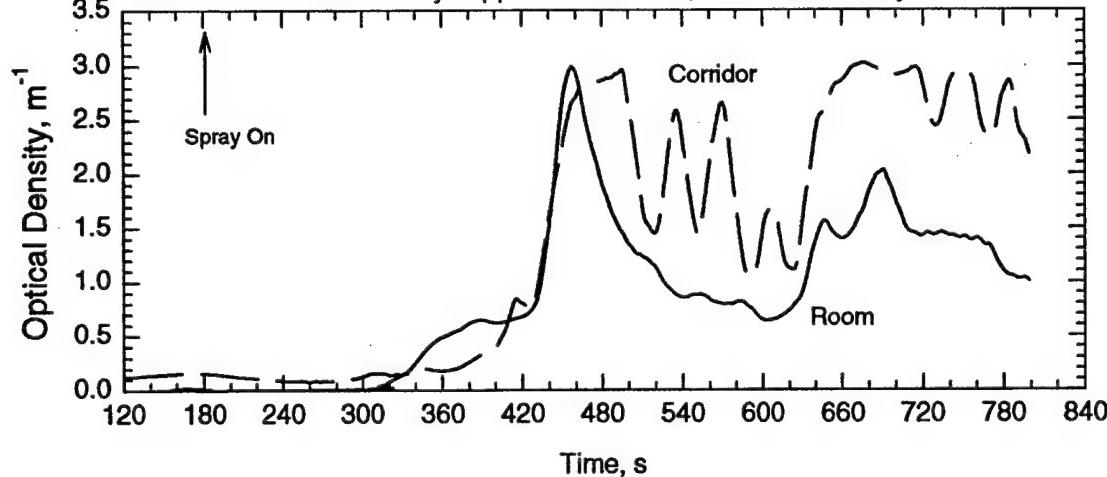


Fig. 25 – Optical density measurements, showing the effect of water spray applied at door; optical density measured in ceiling-mounted “smoke wells”

provide unambiguous evidence that the water mist was materially improving visibility through ‘scrubbing’ of the smoke.

It is expected that unsuppressed fires are smokier than suppressed fires, if for no other reason than that unsuppressed burning produces more soot, entrains more air, and the hot buoyant gases expand the smoke into much larger volumes. Where fire is suppressed by water mist, the soot generation rate will be reduced, and the entrainment of air and volumetric expansion of smoke will be reduced as the temperature. Therefore, that water mist has a beneficial, mitigating effect on the overall hazard presented by smoke, is generally evident. That reduced optical density of smoke can be attributed to ‘scrubbing’ and direct removal of soot particles by water mist, is less clear. Many factors affect visibility in suppressed fire conditions. The continuous generation of steam as water is applied to hot surfaces around a shielded fire, for one example, could overwhelm any visibility benefit due to wash-out of particles.

With suppressed, shielded fires burning in poorly ventilated conditions, carbon monoxide is generated. The carbon monoxide concentration in the smoke produced during a suppressed fire in a berthing space on a ship, could attain dangerous levels in excess of 5000 ppm. This toxic gas is insoluble, and would not be ‘scrubbed’ from smoke by water mist nozzles.

Based on the evidence of the Task 2 fire testing, the following statements can be made:

- (a) Water mist has a significant mitigating effect on smoke conditions during a fire, by reducing the amount of fuel burned and soot generated, reducing buoyancy and smoke spread, and eliminating the danger of fire spread as hot gases spread;
- (b) Visibility in corridors may or may not be improved as a result of the injection of water mist into a compartment fire; visibility is likely to be more influenced by the type of fuel, the elevation of the neutral plane, the presence of steam, etc.; and
- (c) Smoke generated during a suppressed, deep seated fire in a poorly ventilated compartment may have a high concentration of carbon monoxide. CO is not soluble in water and will not be removed by passing through a water mist screen.

3.7 Design Options for Flashover Suppression

The full-scale test series has provided data that can be used to develop a first-order guideline for design of a water mist system for certain types of spaces on a ship. The following recommendations assume a single-deck height (2.5 m) berthing-type space with Class A combustibles, and typical navy door ventilation.

- 3.7.1 Flashover suppression can be achieved in ventilation limited spaces up to 60 m³ in volume, 2.5 m ceiling height, using nozzles over door openings only. Larger volume compartments should include nozzles distributed in the interior of the compartment. The

objective is to use the spray to prevent stratification, and mix hot gases with water mist as much as possible.

- 3-7.2 Nozzles installed in the ceiling of the compartment do a better job of overall cooling than nozzles installed over the doors only. Nozzles can be widely spaced, without regard for overlapping spray cones. A conservative design rule would be to require the sum of the spray cone areas to be at least 20 percent of the total floor area.
- 3-7.3 For the same flow rate per compartment, high pressure nozzles perform measurably better than low pressure nozzles at mixing and cooling gases inside the compartment. They are also more likely to achieve extinguishment.
- 3-7.4 A system designed for flashover suppression will also provide boundary cooling advantages, in that the compartment of fire origin is prevented from getting hot enough for conducted heat to ignite material in one or more adjacent compartments. Deep-seated, shielded fire against bulkheads may create local hot spots which could lead to fire spread across one particular bulkhead.
- 3-7.5 A water mist system designed for flashover suppression will not perform better, necessarily, if activated earlier. Since it may not extinguish the fire, but will prevent it from getting dangerously large, early activation is not critical to performance.
- 3-7.6 The water mist system could be activated on temperature sensor data, as groups of nozzles, or by thermal release of individual nozzles nearest the fire.
- 3-7.7 Average temperature conditions in a compartment during a prolonged suppressed fire scenario could be monitored intelligently by measuring compartment pressure relative to adjacent spaces. The pressure reading would be less variable than individual thermal sensors.

4.0 SUMMARY

The results of these experiments indicate that water mist systems can be highly effective fire suppression systems. Automation of such systems in conjunction with other DC-ARM projects could result in low water flow, low weight impact systems that could readily meet a range of fire suppression objectives. One key to successful integration is the ability to control individual nozzles or groups of nozzles in response to changing environmental and tactical conditions. This requires the use of small diameter tubing and low power consumption flow control devices in addition to reflexive system elements. The key requirement for low flow systems can be met with water mist technology.

The results of these tests do not apply to all water mist technology available. They are applicable to the particular nozzles and system parameters tested, but do not necessarily reflect best available technology with respect to system flow requirements, pressure, or nozzle spacing. Optimization of these parameters in addition to a proposed system architecture and control system is required.

The technology does require testing against a wider range of fire threats, compartment sizes, and ventilation conditions. Such testing is proposed to be conducted in conjunction with DC-ARM Demonstration Testing on the ex-USS SHADWELL.

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